ORBITAL TRANSFER VEHICLE

CONCEPT DEFINITION AND SYSTEMS ANALYSIS STUDY

FINAL REPORT – PHASE I
VOLUME II, BOOK 4

OPERATIONS AND PROPELLANT LOGISTICS
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ORBITAL TRANSFER VEHICLE

CONCEPT DEFINITION

AND

SYSTEM ANALYSIS STUDY

Final Report

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LAUNCH AND FLIGHT OPERATIONS

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FOREWORD

This final report of the Orbital Transfer Vehicle (OTV) Concept Definition and System Analysis Study was prepared by Boeing Aerospace Company for the National Aeronautics and Space Administration's George C. Marshall Space Flight Center in accordance with Contract NAS8-36107. The study was conducted under the direction of the NASA OTV Study Manager, Mr. Donald Saxton and during the period from August 1984 to September 1986.

This final report is organized into the following nine documents:

VOL.	I	Executive Summary (Rev. A)
VOL.	II	OTV Concept Definition & Evaluation
		Book 1 - Mission Analysis & System Requirements
		Book 2 - Selected OTV Concept Definition - Phase I
		Book 3 - Configuration and Subsystem Trade Studies
		Book 4 - Operations and Propellant Logistics
VOL.	III	System & Program Trades
VOL.	IV	Space Station Accommodations
VOL.	V	WBS & Dictionary
VOL.	VI	Cost Estimates
VOL.	VII	Integrated Technology Development Plan
VOL.	VIII	Environmental Analysis
VOL.	IX	Implications of Alternate Mission Models and Launch Vehicles

The following personnel were key contributors during the conduct of the study in the disciplines shown:

Study Manager	E. Davis (Phase I-3rd and 4th Quarters and Phase II)
	D. Andrews (Phase I-1st and 2nd Quarters)
Mission & System Analysis	J. Jordan, J. Hamilton
Configurations	D. Parkman, W. Sanders, D. MacWhirter

Propulsion	W. Patterson, L. Cooper, G. Schmidt
Structures	M. Musgrove, L. Duvall, D. Christianson, M. Wright
Thermal Control	T. Flynn, R. Savage
Avionics	D. Johnson, T. Moser, R.J. Gewin, D. Norvell
Electrical Power	R.J. Gewin
Mass Properties	J. Cannon
Reliability	J. Reh
Aerothermodynamics	R. Savage, P. Keller
Aeroguidance	J. Bradt
Aerodynamics	S. Ferguson
Performance	M. Martin
Launch Operations	J. Hagen
Flight Operations	J. Jordan, M. Martin
Propellant Logistics	W. Patterson, L. Cooper, C. Wilkinson
Station Accommodations	D. Eder, C. Wilkinson
Cost & Programmatics	D. Hasstedt, J. Kuhn, W. Yukawa
Documentation Support	T. Sanders, S. Becklund

For further information contact:

Don Saxton
NASA MSFC/PF20
MSFC, AL 35812
(205) 544-5035

Eldon E. Davis
Boeing Aerospace Company. M/S 8C-59
P.O. Box 3999
Seattle, WA 98124-2499
(206) 773-6012

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ACRONYMS AND ABBREVIATIONS

ACC	Aft Cargo Carrier
AFE	Aeroassist Flight Experiment
AGE	Aerospace Ground Equipment
AL	Aluminum
ASE	Airborne Support Equipment
A/T	Acceptance Test, Auxiliary Tank
AUX	Auxiliary
AVG	Average
B/B	Ballute Brake
B/W	Backwall
CDR	Critical Design Review
CPU	Central Processing Unit
CUM	Cumulative
DAK	Double Aluminized Kapton
DDT&E	Design, Development, Test & Evaluation
DELIV	Delivery
DMU	Data Management Unit
DoD	Department of Defense
EPS	Electrical Power System
FACIL	Facility
FFC	First Flight Certification
FLTS	Flights
FOSR	Flexible Optical Surface Reflector
FRCI	Fiber Refractory Composite Insulation
F.S.	Fail Safe
FSI	Flexible Surface Insulation
FTA	Facilities Test Article
GB	Ground Based
GEO	Geostationary Earth Orbit
GPS	Global Positioning System
GRD	Ground
IOC	Initial Operational Capability
IRU	Inertial Reference Unit
IUS	Inertial Upper Stage

JSC	Johnson Space Center
L/B	Lifting Brake
LCC	Life Cycle Cost
L/D	Lift to Drag
MGSS	Mobile GEO Service Station
MLI	Multilayer Insulation
MPS	Main Propulsion System
MPTA	Main Propulsion Test Article
MSFC	Marshall Space Flight Center
OMV	Orbital Maneuvering Vehicle
OPS	Operations
OTV	Orbital Transfer Vehicle
PAM	Payload Assist Module, Propulsion Avionics Module
PDR	Preliminary Design Review
PFC	Preliminary Flight Certification
P/L	Payload
PROD	Production
PROP	Propellant
RCS	Reaction Control System
REF	Reference
RGB	Reusable Ground Based
R&R	Remove & Replace
RSB	Reusable Space Based
RSI	Reusable Surface Insulation
SB	Space Based
S/C	Spacecraft
SCB	Shuttle Cargo Bay
SIL	Systems Integration Laboratory
STA	Structural Test Article
STG	Stage
STS	Space Transportation System
T/D	Turndown
TDRS	Tracking Data Relay Satellite
TPS	Thermal Protection System
TT&C	Telemetry, Tracking and Control
WBS	Work Breakdown Structure

1.0 INTRODUCTION

This section provides a description of the study in terms of background, objectives, issues, organization of study and report, and the content of this specific volume.

Use of trade names, names of manufacturers, or recommendations in this report does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

And finally, it should be recognized that this study was conducted prior to the STS safety review that resulted in an STS position of "no Centaur in Shuttle" and subsequently an indication of no plans to accommodate a cryo OTV or OTV propellant dump/vent. The implications of this decision are briefly addressed in section 2.2 of the Volume I and also in Volume IX reporting the Phase II effort which had the OTV launched by an unmanned cargo launch vehicle. A full assessment of a safety compatible cryo OTV launched by the Shuttle will require analysis in a future study.

1.1 BACKGROUND

Access to GEO and earth escape capability is currently achieved through the use of partially reusable and expendable launch systems and expendable upper stages. Projected mission requirements beyond the mid-1990's indicate durations and payload characteristics in terms of mass and nature (manned missions) that will exceed the capabilities of the existing upper stage fleet. Equally important as the physical shortfalls is the relatively high cost to the payload. Based on STS launch and existing upper stages, the cost of delivering payloads to GEO range from $12,000 to $24,000 per pound.

A significant step in overcoming the above factors would be the development of a new highly efficient upper stage. Numerous studies (ref. 1, 2, 3, 4) have been conducted during the past decade concerning the definition of such a stage and its program. The scope of these investigations have included a wide variety of system-level issues dealing with reusability, the type of propulsion to be used, benefits of aeroassist, ground- and space-basing, and impact of the launch system.

1.2 OBJECTIVES AND ISSUES

The overall objective of this study was to re-examine many of these same issues but within the framework of the most recent projections in technology readiness, realization that a space station is a firm national commitment, and a refinement in mission projections out to 2010.

During the nineteen-month technical effort the specific issues addressed were:

a. What are the driving missions?

b. What are the preferred space-based OTV characteristics in terms of propulsion, aeroassist, staging, and operability features?

c. What are the preferred ground-based OTV characteristics in terms of delivery mode, aeroassist, and ability to satisfy the most demanding missions?

d. How extensive are the orbital support systems in terms of propellant logistics and space station accommodations?

e. Where should the OTV be based?

f. How cost effective is a reusable OTV program?

g. What are the implications of using advanced launch vehicles?

1.3 STUDY AND REPORT ORGANIZATION

Accomplishment of the objectives and investigation of the issues was done considering two basic combinations of mission models and launch systems. Phase I concerned itself with a mission model having 145 OTV flights during the 1995-2010 timeframe (Revision 8 OTV mission model) and relied solely on the Space Shuttle for launching. Phase 2 considered a more ambitious model (Rev. 9) having 442 flights during the same time frame as well as use of a large unmanned cargo launch vehicle and an advanced Space Shuttle (STS II).

The study is reported in nine separate volumes. Volume I presents an overview of the results and findings for the entire study. Volume II through VIII contains material associated only with the Phase I activity. Volume IX presents material unique to the Phase II activity. Phase I involved five quarters of the technical effort and one quarter was associated with the Phase II analyses.

1.4 DOCUMENT CONTENT

This document reports the work associated with the OTV launch and flight operations and propellant logistics for the SB OTV. The launch processing operations address both GB and SB OTV elements in terms of initial assembly and checkout, as well as the turnaround operations associated with subsequent reuse. Also included is a brief summary of the impact of the KSC OTV Operations Study (Ref. 6). The propellant logistics operations for a SB OTV covers the delivery system, storage system at the space station and implications of the "no vent" rule at the station. The final section discusses typical flight operations associated with an OTV mission.

2.0 LAUNCH PROCESSING OPERATIONS

The primary objective of the launch processing analysis was to reveal discriminators (if any) between given space based and ground based OTV configurations when performing the specified mission model. The figure of merit used in comparing the concepts was man-years or man-hours. It should be emphasized that the data developed is only appropriate for relative comparisons. A cursory review of facility requirements associated with the OTV concepts was also performed.

2.1 GROUND BASED ORBITAL TRANSFER VEHICLE PROCESSING

The Ground Based Orbital Transfer Vehicle (GBOTV) concept includes a main stage, Airborne Support Experiment (ASE), and auxiliary propellant tank. All flights require the use of the main stage hereafter referred to as GBOTV. Thirty-six flights also require the use of the auxiliary propellant tank. This section discusses the processing operations associated with these elements as well as those related to payload and STS integration.

2.1.1 Assumptions/Guidelines/Derived Requirements.

The analysis of the GBOTV launch processing operation is based on the following:

a. The OTV and spacecraft operations do not impact the STS Timeline. Assembly, refurbishment, checkout and spacecraft integration operations will be performed offline to STS operations.
b. The cargo (OTV/Spacecraft) operations on the launch pad are consistent with STS timelines and a parallel operation concept.
c. The OTV will be fueled with LO_2 and LH_2 on the launch pad parallel with STS propellant loading during "Shuttle Launch Countdown".
d. STAR 27 and VSTAR 10 Level III Assessment timelines are used as a general baseline for STS related functions.
e. The OTV is assembled at an off site location and shipped to the launch site in the following subassemblies:
    1. Tank Assembly--includes LH_2 and LO_2 tanks plus an avionics module.
    2. Engine Assembly--two each.
    3. Hypergol Tank Assembly(ies).
    4. Navigation Assembly--IMU.
    5. Aeroassist Device --Ballute.
    6. Airborne Support Equipment.

   7. Miscellaneous Ordnance Devices.

f. The initial fill and passivation of the hypergolic fuel (hydrazine) tanks is performed prior to installing the tanks on the vehicle. Subsequent filling operations are performed in the assembly/checkout/refurbishment facility.

n. The ASE is similar to the ASE defined in the prior Boeing Phase A study, indicated by Reference 1, NAS8-33532.

o. For comparison purpose, assume:
   1. Offline Assembly, Checkout, Refurbishment and Integration Activities are 5 day, 8 hours per shift operations. Shifts will be one or two depending on requirements and will affect total number of personnel required.
   2. Online Launch Pad and Post-landing Operations are 7 day, 12 hours per shift operations.

2.1.2 GBOTV Ground Processing

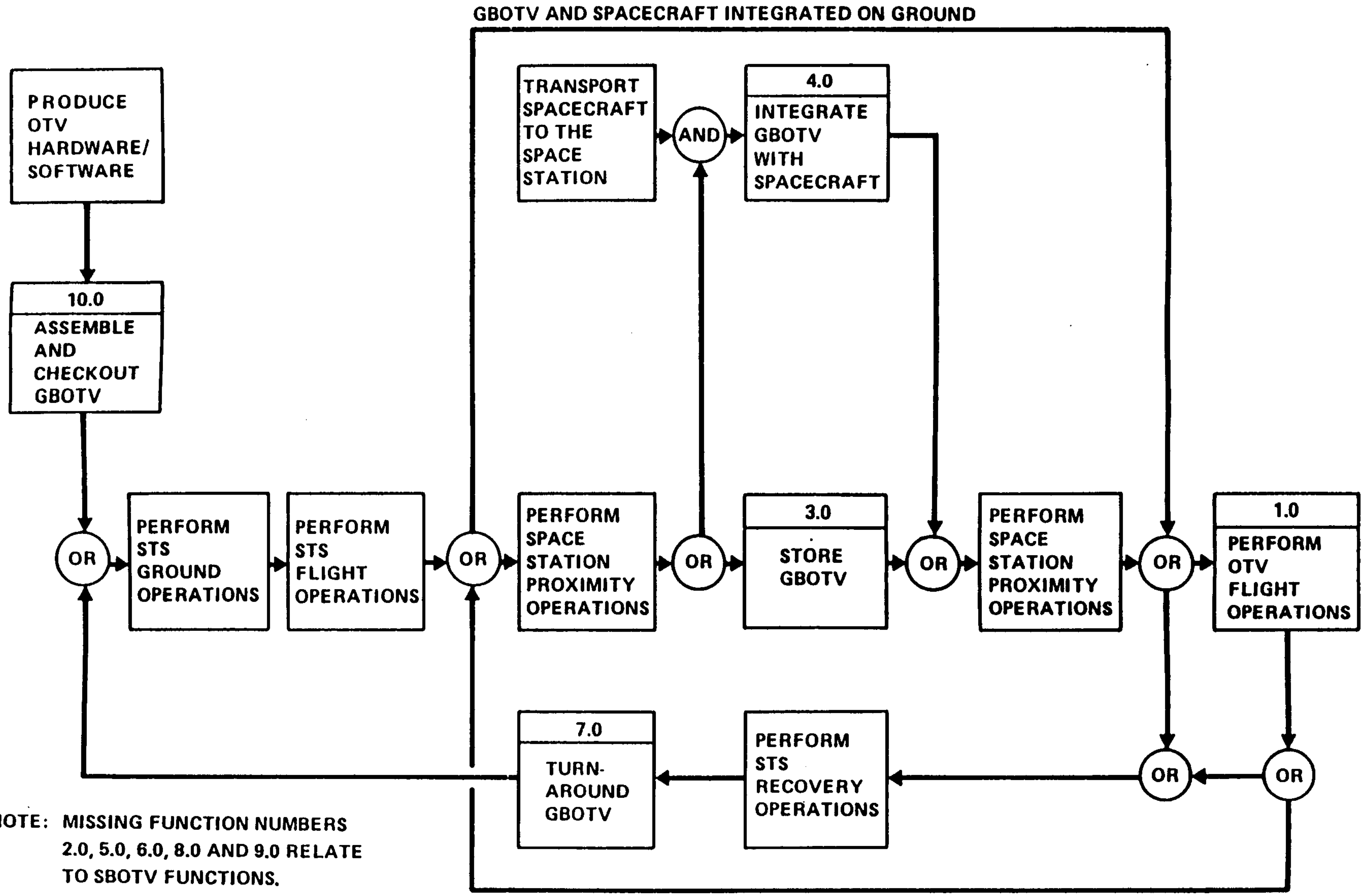
The GBOTV main stage top level functional flow is shown in Figure 2.1.2-1. The option exists to integrate the OTV with a spacecraft either on the ground or at the Space Station. The option exercised is dependent on Orbiter capabilities, OTV capabilities, spacecraft characteristics and mission requirements. The flow envisions an OTV launched from the Orbiter and recovered by the Orbiter although the option does exist to recover at the Space Station. An OTV launched from the Space Station (after OTV/Spacecraft integration) could also be recovered by either the space Station or the Orbiter. The ability of an OTV to adapt to mission requirements is indicated by the operational flow.

2.1.2.1 Processing Plan

Ground processing functions not severely impacted by either STS or spacecraft operations include the Initial Assembly and Checkout and the Refurbishment Operations. The GBOTV ground processing plan is based on an evolution of existing ground processing methods and procedures and envisions that the final design of the vehicle will contain features which facilitate processing. It does contain robotic operations, streamlined testing and off-site assembly consistent with state-of-the-art technology and mature space system operations. Key elements of the plan include:

a. One-time cryogenic tank load/drain operations,

b. Hypergol loading operations offline to STS operations and prior to OTV/Spacecraft integration,



NOTE: MISSING FUNCTION NUMBERS 2.0, 5.0, 6.0, 8.0 AND 9.0 RELATE TO SBOTV FUNCTIONS.

Figure 2.1.2-1 Top-Level GBOTV Operational Functional Flow

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c. One-time Orbiter interface (CITE) verification except for spacecraft integration requirements,
d. Simplification of structural interfaces (spacecraft and auxiliary propellant tanks),
e. Minimization of mechanical and electrical connections at interfaces,
f. Autonomous vehicle self-check with built-in-test equipment, fault analysis and fault isolation,
g. Robotic refurbishment as practical,
h. Assembly and checkout off-site as transportation modes/considerations will allow,
i. Elimination of planned subsystem testing on site and redundant system level testing, and
j. Standardization of test documentation.

2.1.2.2 GBOTV/Spacecraft Processing

Initial Assembly and Checkout Timeline

The timeline associated with the initial assembly and checkout of the GBOTV is presented in Figure 2.1.2-2.

GBOTV/Spacecraft Processing Timelines

The top level operations timeline for the case of the GBOTV and a spacecraft (payload) being launched together is shown in Figure 2.1.2-3. Shuttle related timebars are based on STAR 27, Figure 8, Level III STS Turnaround Assessment and VSTAR 10, Figure 16, Level III Assessed Timeline. The Refurbishment timebar is an estimate based on the configuration and characteristics of the GBOTV known at this time. The Integration and PCR timebars are derived from past IUS/spacecraft processing experience. Processing of a given OTV is estimated to last approximately 8 weeks using primarily two shift operations. To satisfy the low model OTV flight rate of 12 per year ($4\frac{1}{2}$ week flight centers), two parallel processing lines are used.

Further breakdown on the post landing operations is presented in Figure 2.1.2-4.

Additional detail on the top level refurbishment timebar is shown in Figure 2.1.2-5. The key tasks involved in the refurbishment operations include: (a) Safing the Propulsion and Reaction Control systems, (b) Inspection and maintenance of the Main Propulsion System, (c) Functional check of the Avionics subsystems, (d) Servicing of the storables, and (e) Installation of a new ballute.

The most significant timebar in the refurbishment operations is the "Maintain and Service Engines and Main Propulsion System." This timebar of 40 hours is somewhat

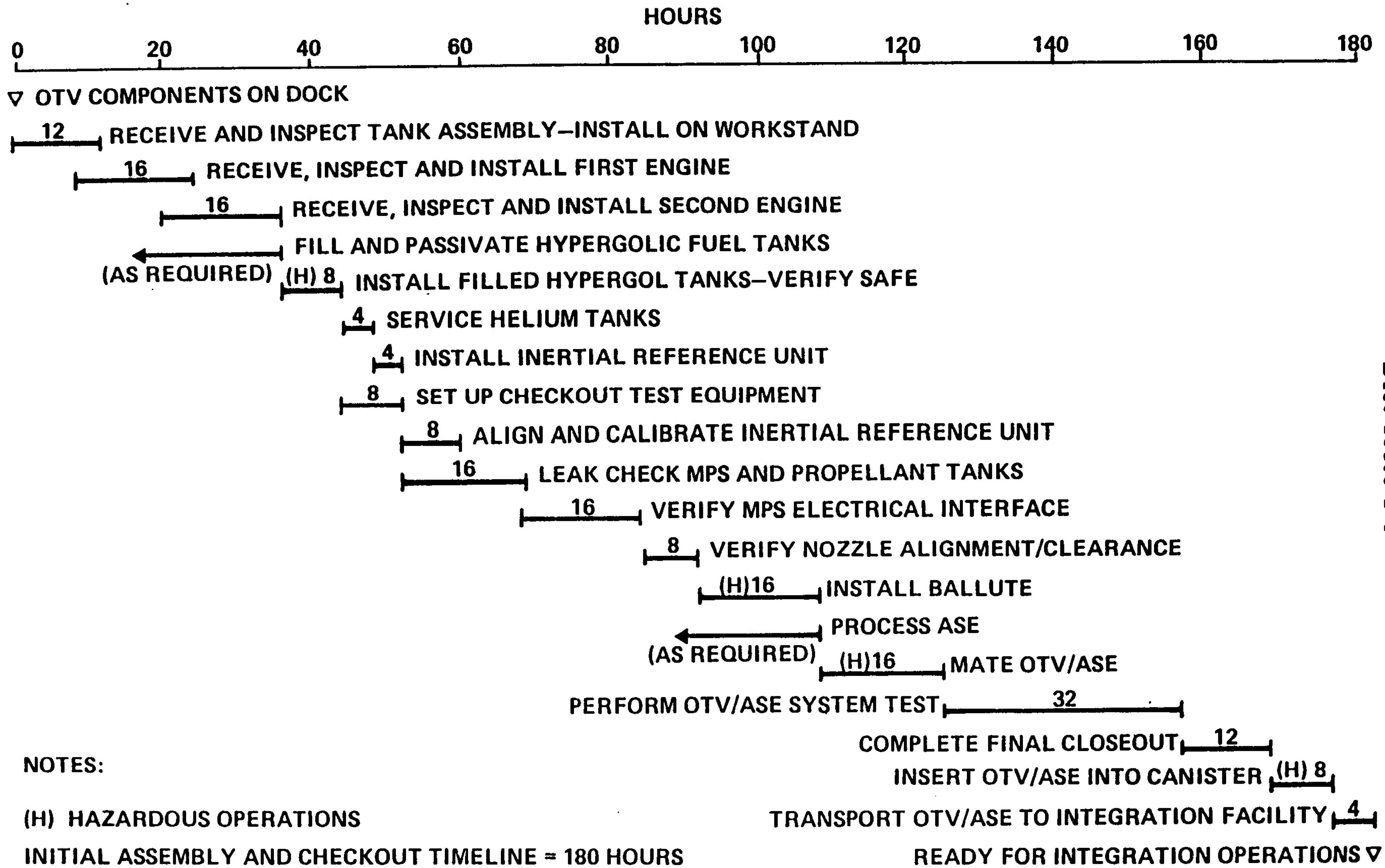

Figure 2.1.2-2 GBOTV Initial Assembly and Checkout

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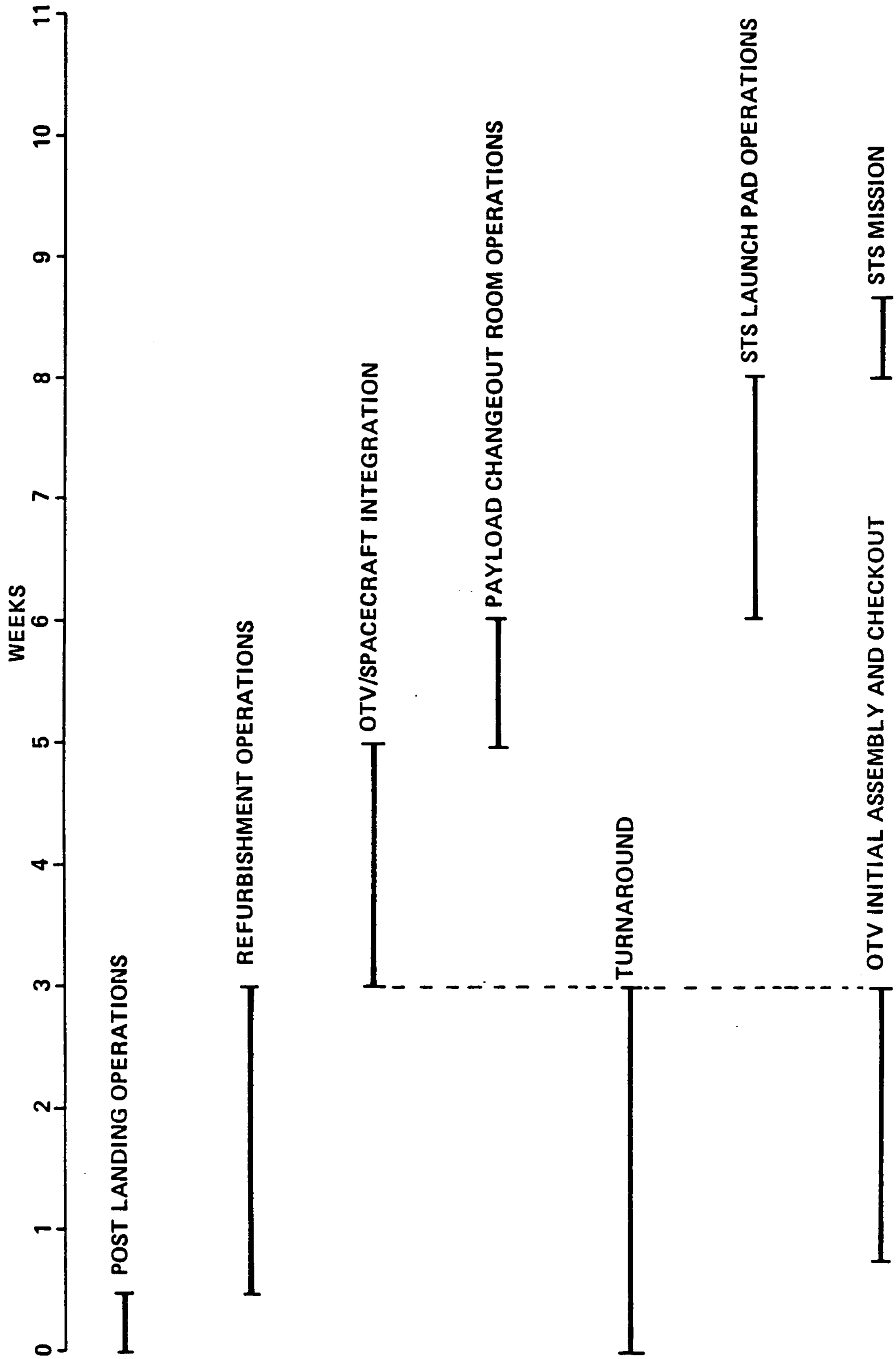

Figure 2.1.2-3 Ground Based OTV Operations Timeline

OTV-613

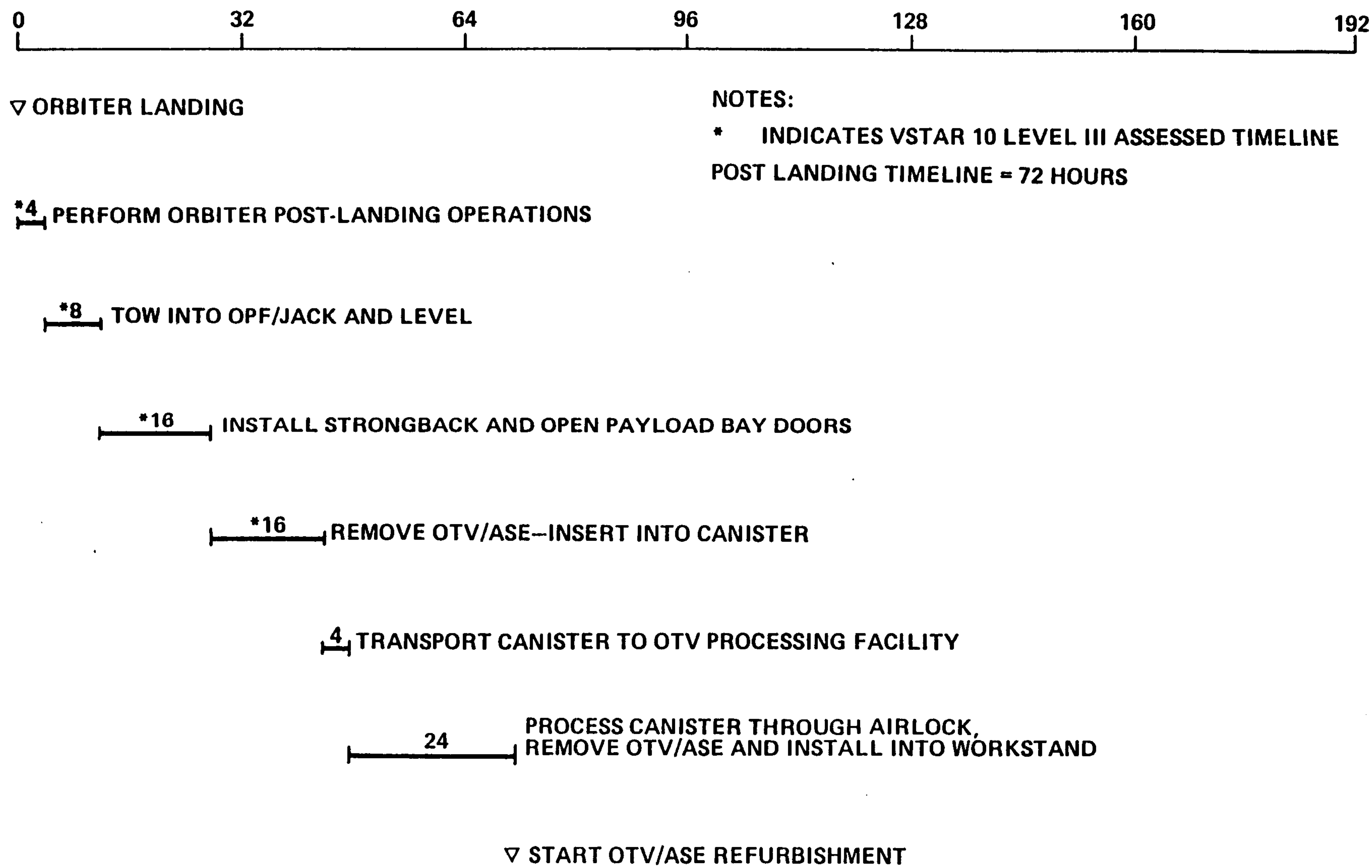

Figure 2.1.2-4 Post Landing Operations

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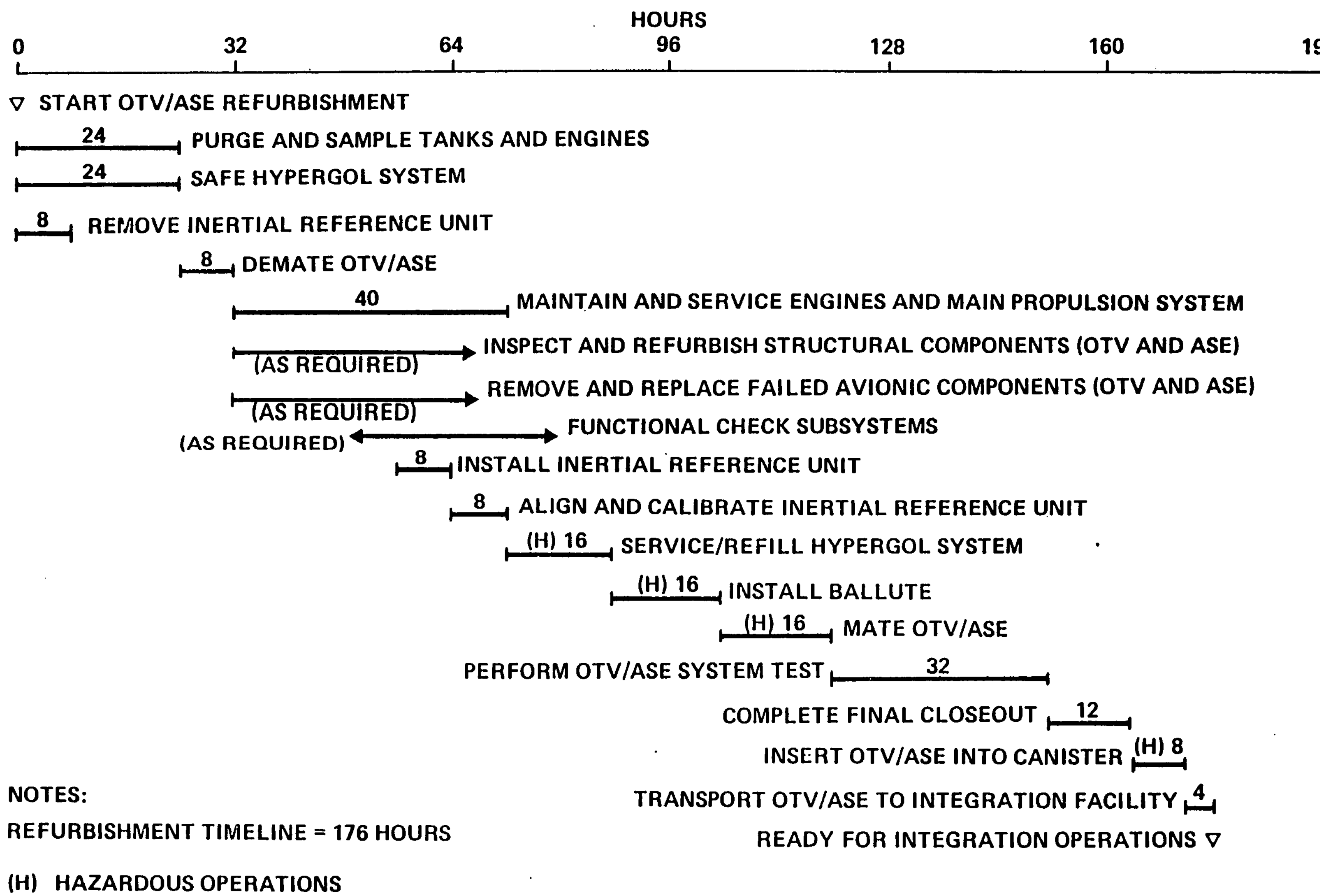

Figure 2.1.2-5 GBOTV Refurbishment Operations

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arbitrary. It allows for trouble shooting the subsystem (8 hours), changeout of a complete engine (16 hours), a subsystem checkout (8 hours) and servicing (8 hours). This scenario merely substantiates the 40 hour timebar and is but one of many possible maintenance scenarios. All other refurbishment and maintenance activities except for servicing the hypergol system is accomplished in parallel with and within the same timebar. A more rigorous analysis, after knowledge of the actual OTV hardware is available, should be accomplished.

A breakdown of the major tasks associated with GBOTV/spacecraft integration timeline is presented in Figure 2.1.2-6. Further detail on the operations timeline dealing with OTV/Spacecraft integration with the STS Orbiter is shown in Figure 2.1.2-7.

Processing Effort and Organization

The processing effort expressed in terms of calendar time is shown in Table 2.1.2-1. The calendar time of 7.68 weeks per flight supports the maximum requirement of 12 OTV missions per year with two OTV processing lines.

The organizations and headcount to support the two processing lines on a two shift basis is shown in Table 2.1.2-2. The data is based on a launch site support organization developed during a previous OTV Concept Definition Study of Reference 1. (Document D180-26090-2, Final Report OTV Concept Definition Study, Volume 2, Mission Analysis and operations, 1980.) The previously developed organization was modified, primarily by increasing the numbers of engineers, technicians, planners and inspectors necessary to support two shift, two line operations resulting in a 92 person organization.

The processing effort required after an OTV flight is estimated to require 10.5 man years. The methodology used to arrive at per flight costs is as follows:

a. The general tasks are assigned a work schedule. Post Landing and STS Launch Pad Operations are on a 7 day/12 hour schedule. All other operations are on 5 day/8 hour schedule. All operations are worked on a two shift basis.

b. The timeline hours are converted to calendar weeks either by dividing by 168 for the 7/12 schedule or 80 for the 5/8 schedule.

c. The calendar weeks associated with the 7/12 schedule are modified by a factor of 2.65 to account for overtime.

$$\frac{40 + 44(1.5)}{40} = 2.65$$

d. The year is assumed to have 50 weeks (vacation, holidays, and roundoff).

e. The 92 person organization supports each processing line equally (divide by 2).

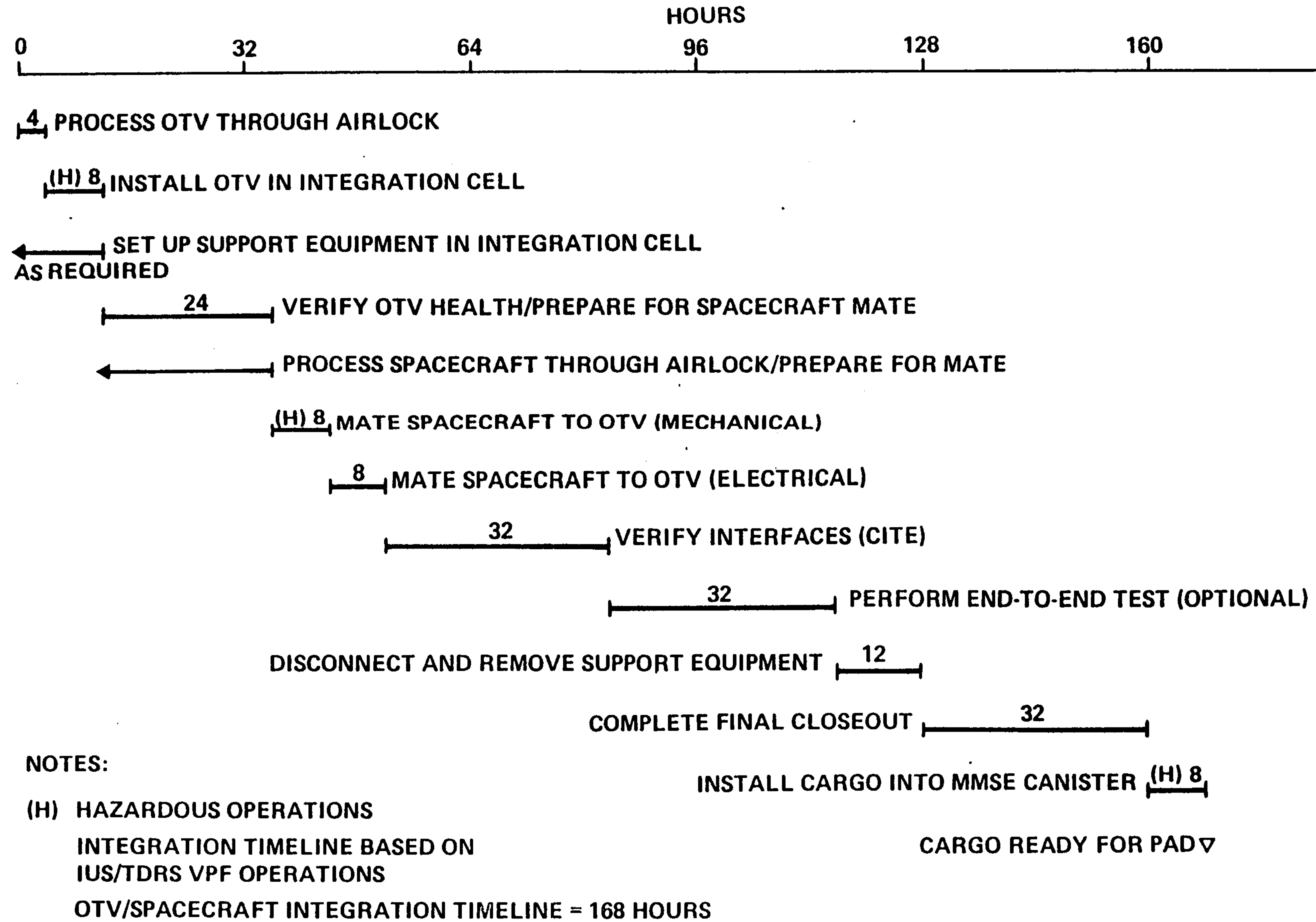

Figure 2.1.2-6 GBOTV/Spacecraft Integration

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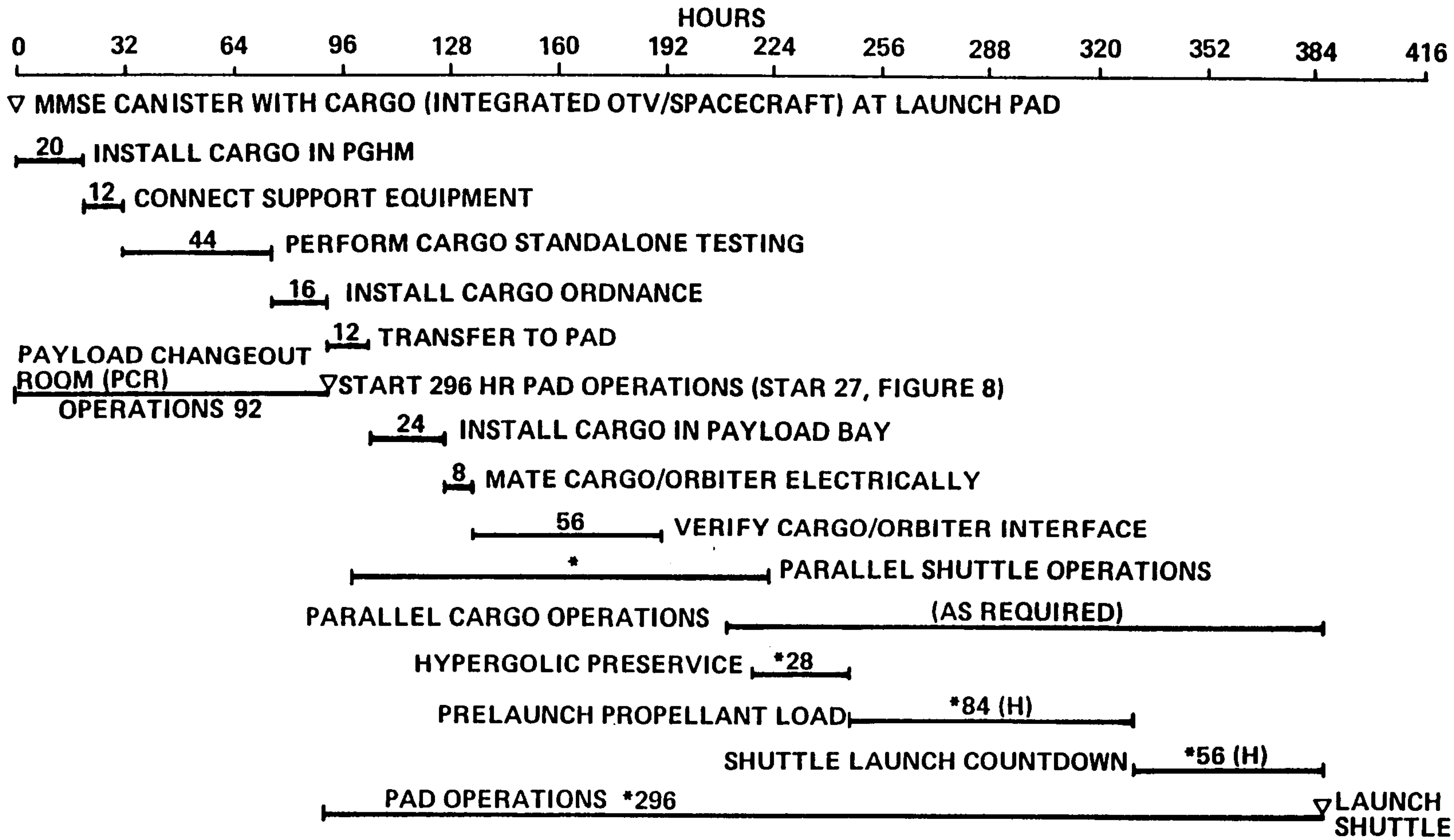

PCR TIMELINE (OFFLINE) = 92 HOURS

CARGO OPERATIONS TIMELINE (ON LINE)= 88 HOURS

*STAR 27, FIGURE 8, LEVEL III STS TURNAROUND ASSESSMENT

NOTES:

(H) HAZARDOUS OPERATIONS

Figure 2.1.2-7 OTV/Spacecraft/Orbiter Integration

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Table 2.1.2-1. Ground-Based OTV Ground Processing Effort

MAJOR ACTIVITY	WORK SCHEDULE [1]	NUMBER OF SHIFTS	PROCESSING TIMELINE HOURS (SERIAL)	CALENDAR WEEKS PER FLIGHT
INITIAL ASSEMBLY AND CHECKOUT	5 x 8	2	180	2.25
← TURNAROUND →				
POST LANDING OPERATIONS	7 x 12	2	72	0.43**
REFURBISHMENT OPERATIONS	5 x 8	2	176	2.20
OTV TANK/SPACECRAFT INTEGRATION	5 x 8	2	168	2.10
PAYLOAD CHANGEOUT ROOM OPERATIONS	5 x 8	2	92	1.15
STS LAUNCH PAD OPERATIONS	7 x 12	2	296	1.8*
TURNAROUND	---	---	TOTAL	7.68

*EQUIVALENT 5 x 8 TIME EQUALS 4.77 CALENDAR WEEKS

**EQUIVALENT 5 x 8 TIME EQUALS 1.14 CALENDAR WEEKS

[1] DAYS PER WEEK X HOURS PER DAY

OTV-1746

Table 2.1.2-2 Ground Based OTV Ground Processing Organization

SKILL CLASSIFICATION	HEADCOUNT	PERCENTAGE OF TOTAL	HEADCOUNT BREAKDOWN
ADMINISTRATION (CONTRACTS, FINANCE, PERSONNEL, PROCUREMENT)	3	3.3	CONTRACT ADMINISTRATION (1), FINANCE/PERSONNEL (1), PROCUREMENT (1)
DATA PROCESSING (COMPUTER SPECIALISTS, DATA ENTRY)	1	1.1	COMPUTER TECHNICIAN/ PROCESSOR (1)
ENGINEERING (ENGINEERS, DRAFTING, ASSOCIATE ENGINEERS)	27	29.3	TEST AND CHECKOUT (2x2x6=24) SUPPORT (3)
LOGISTICS (STOREKEEPERS, SHIPPING AND RECEIVING, DRIVERS)	4	4.3	SHIPPING AND RECEIVING (1), STOREKEEPER (2), DRIVER (1)
MANAGEMENT (MANAGEMENT AND SUPERVISION)	4	4.3	MANAGER (1), RECEPTIONIST (1), SUPERVISOR (2)
OPERATIONS PLANNING (PLANNERS, SCHEDULERS, ANALYZERS, DOCUMENTATION)	7	7.6	PP&C (1), PLANNERS (4), ANALYST (2)
QUALITY/INSPECTOR (CONFIGURATION MANAGEMENT, QUALITY ASSURANCE)	10	10.9	TEST AND CHECKOUT (2x2x2=8) CONFIGURATION CONTROL (1) LOGISTICS INSPECTOR (1)
TECHNICIANS (MECHANICAL AND ELECTRICAL TECHNICIANS, EQUIPMENT OPERATORS, FUELS SPECIALISTS)	36	39.2	TEST AND CHECKOUT (2x2x9=36)
TOTAL	92	100	

OTV-588

f. The equivalent calendar work weeks are summed, divided by 50 and multiplied by 92/2 to arrive at the manpower requirement.

Example:

OTV integrated with Spacecraft

$$\frac{(0.43)(2.65) + 2.20 + 2.10 + 1.15 + 1.8(2.65)}{50} \cdot \frac{92}{2} = 10.5 \text{ man-years/flight}$$

2.1.2.3 Separate Processing for GBOTV and Spacecraft

This scenario occurs when the OTV/Spacecraft combination exceeds the STS capability in either weight or length. Based on the Rev. 8 mission model and performance capability of the GBOTV, length will be the key factor. For this case, the GBOTV and spacecraft will be launched separately. GBOTV ground processing for this scenario has the following changes relative to figure 2.1.2-3: deletion of the OTV/Spacecraft Integration timebar, deletion of any spacecraft operations in the Payload Changeout Room Operations and the addition of an OTV/Spacecraft interface verification, using a spacecraft simulator, to the Refurbishment Operations. For this analysis, the reduced processing effort in the Payload Changeout Room is considered equivalent to the increased effort caused by the OTV/Spacecraft interface verification. The resulting processing effort is 8.5 man years for the OTV and 11.0 man years for the spacecraft.

2.1.3 GBOTV/Auxiliary Propellant Tank Ground Processing

Auxiliary propellant tanks are required when the main stage does not have sufficient performance capability for a given payload. Based on the Rev. 8 mission model, the combined weight of the main stage and auxiliary tank preclude launching both on a single STS flight. Selection of the preferred auxiliary propellant tank option for the GBOTV concept involved the consideration of both expendable and reusable tanks. The expendable concept involved two tanks each containing LO_2 and LH_2 and attached to the side of the main stage. The reusable concept involved a single LO_2/LH_2 tank and was attached above the main stage. The ground processing effort in support of this trade evaluated both tank options in potential combinations with the main stage and spacecraft (payload).

2.1.3.1 Processing Plan

Key elements of the auxiliary tank ground processing plan include:

a. Processing is parallel to GBOTV processing and is performed in the same facility.

b. The auxiliary tanks will be verified as compatible with the OTV prior to shipment to the launch site. The auxiliary tanks arrive on the launch site as complete assemblies including LO_2 tank, Helium tank(s) and associated plumbing.
c. The auxiliary tanks are designed to be attached to an ASE which is refurbishable and reusable, supports the tanks in the Orbiter Bay and provides LH_2 and LO_2 fill plumbing.
d. The tank-to-OTV plumbing interfaces are "quick disconnect." The tank-to-OTV structural interface is a "pinned" connection.
e. The GBOTV ground processing organization is supplemented with the following auxiliary tank processing manpower: engineers (2), inspectors (2), and technicians (8) for a total of 12 additional people.

2.1.3.2 Processing Combinations

As indicated earlier, several processing combinations of OTV, spacecraft, and auxiliary tank were evaluated. A description of each combination follows.

OTV/Spacecraft, Expendable Tank Set

This scenario occurs when OTV main stage does not have enough propellant to satisfy the payload requirements. It involves launching the expendable tanks on a separate flight. The OTV and spacecraft are processed normally. The tanks are mated to the OTV in space.

Figure 2.1.3-1 depicts the timeline for expendable auxiliary tank set ground processing. The processing involves a mating of the tanks to the ASE, an interface verification, an integration with the Orbiter and support of an STS launch. Table 2.1.3-1 translates the timeline into calendar weeks based on two shifts with the indicated work schedule. The two shifts are not necessarily required to meet the mission requirements. The primary rationale for the two shift operation is to maintain consistency with the GBOTV analysis.

OTV Only, Reusable Auxiliary Tank Plus Spacecraft

This scenario occurs when the OTV plus auxiliary propellant (APT) exceed STS limits but the APT plus payload do not. It requires an OTV-to-APT/Spacecraft mating in space. The tank module interfaces with the OTV at the normal OTV-to-Spacecraft interface and provides the appropriate "flow-through" plumbing, data circuits and electrical circuits. The APT interfaces with the spacecraft in a manner identified to

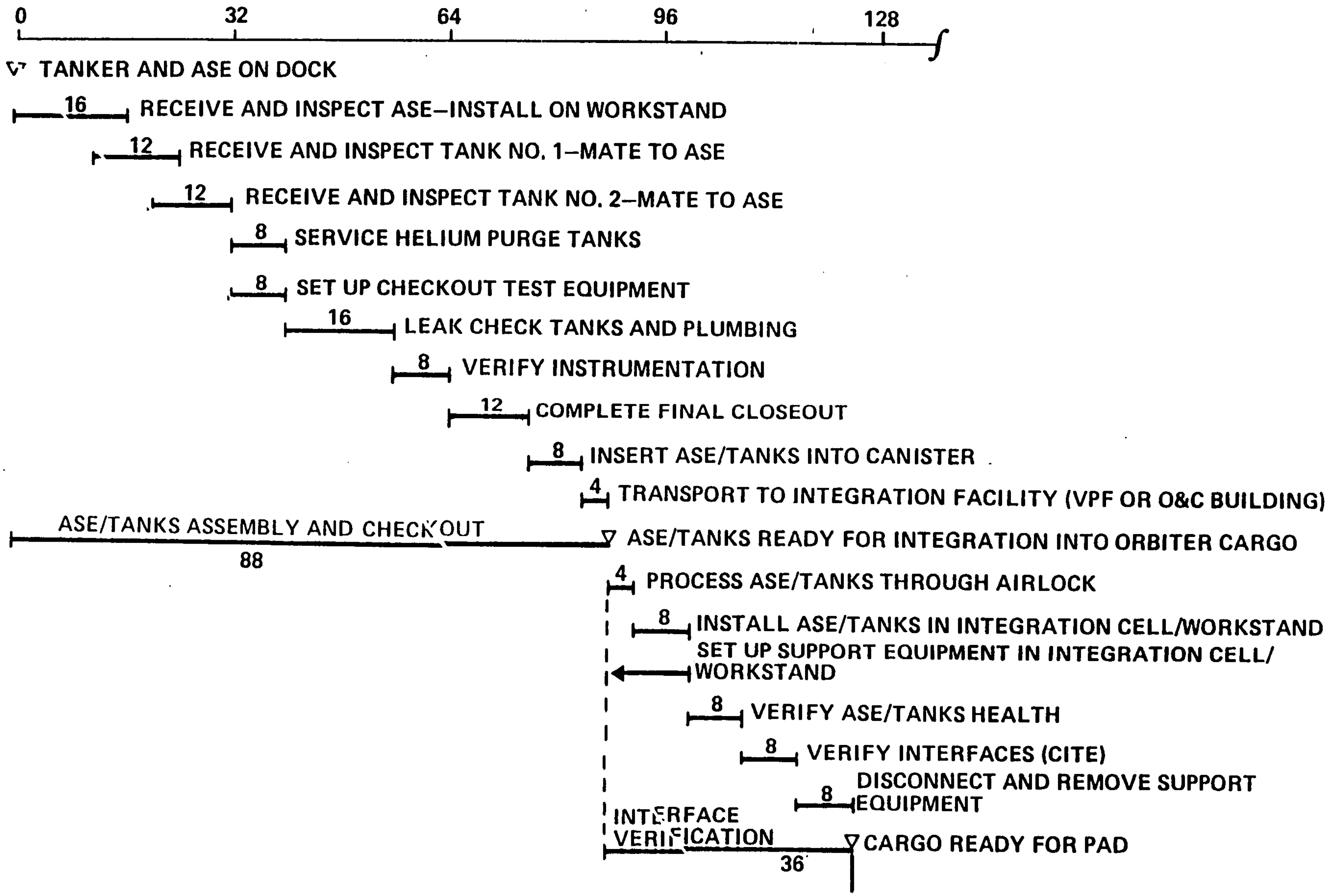
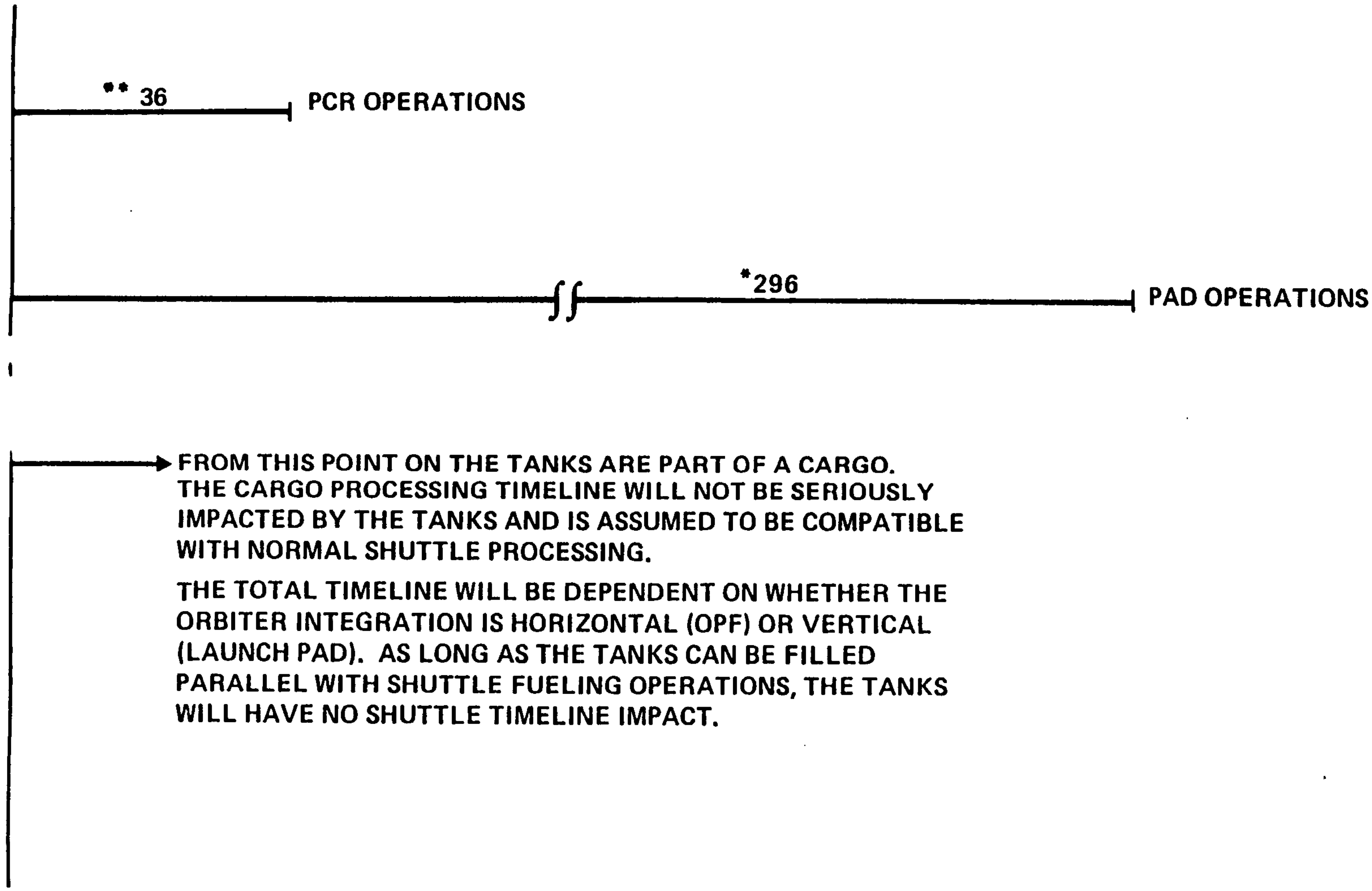


Figure 2.1.3-1 Expendable Auxiliary Tank Ground Processing

OTV-630



*STAR 27, FIGURE 8, LEVEL III STS TURNAROUND ASSESSMENT

**FROM SBOTV TANKER ANALYSIS

Figure 2.1.3-1 Expendable Auxiliary Tank Ground Processing (Continued)

OTV-631

Table 2.1.3-1 Ground Based OTV Expendable Tanks Ground Processing Effort

MAJOR ACTIVITY	WORK SCHEDULE	NUMBER OF SHIFTS	TIMELINE HOURS	CALENDAR WEEKS PER FLIGHT
INITIAL ASSEMBLY AND CHECKOUT	5 x 8	2	88	1.10
INTERFACE VERIFICATION	5 x 8	2	36	0.45
PAYLOAD CHANGEOUT ROOM OPERATIONS	5 x 8	2	36	0.45
STS LAUNCH PAD OPERATIONS	7 x 12	2	296	1.8*
	---	---	TOTAL	3.8

*EQUIVALENT 5 x 8 TIME EQUALS 4.77 CALENDAR WEEKS

OTV-575

the OTV. An ASE is required to support the filled APT plus the spacecraft and to provide the Orbiter Bay to Cargo interfaces.

Essentially two processings involving OTV operations are required to get one OTV/Reusable APT/Spacecraft into LEO. Figure 2.1.3-2 depicts the timeline for the initial flight of an APT. The processing is identical to a GBOTV processing except for the initial assembly and checkout. The tank has no engines or avionics resulting in considerably less checkout processing. During the spacecraft integration and STS operations; however, the APT and ASE must perform all the functions that the OTV and ASE perform during similar operations. The timeline for these operations is essentially identical.

Figure 2.1.3-3 depicts the processing required to turnaround the APT after the first flight. The APT returns to earth as part of the GBOTV. It is demated from the OTV, refurbished and mated to it's ASE. The turnaround timeline includes a subsequent spacecraft integration and STS Launch.

Table 2.1.3-2 translates the timelines into calendar weeks using shifts and work schedules consistent with the GBOTV analysis. Due to spacecraft integration and STS Launch Pad operations the calendar time for processing the APT is comparable to that for the GBOTV. However, the manpower expended is considerably less.

OTV Only, Spacecraft Plus Expendable Tank Set

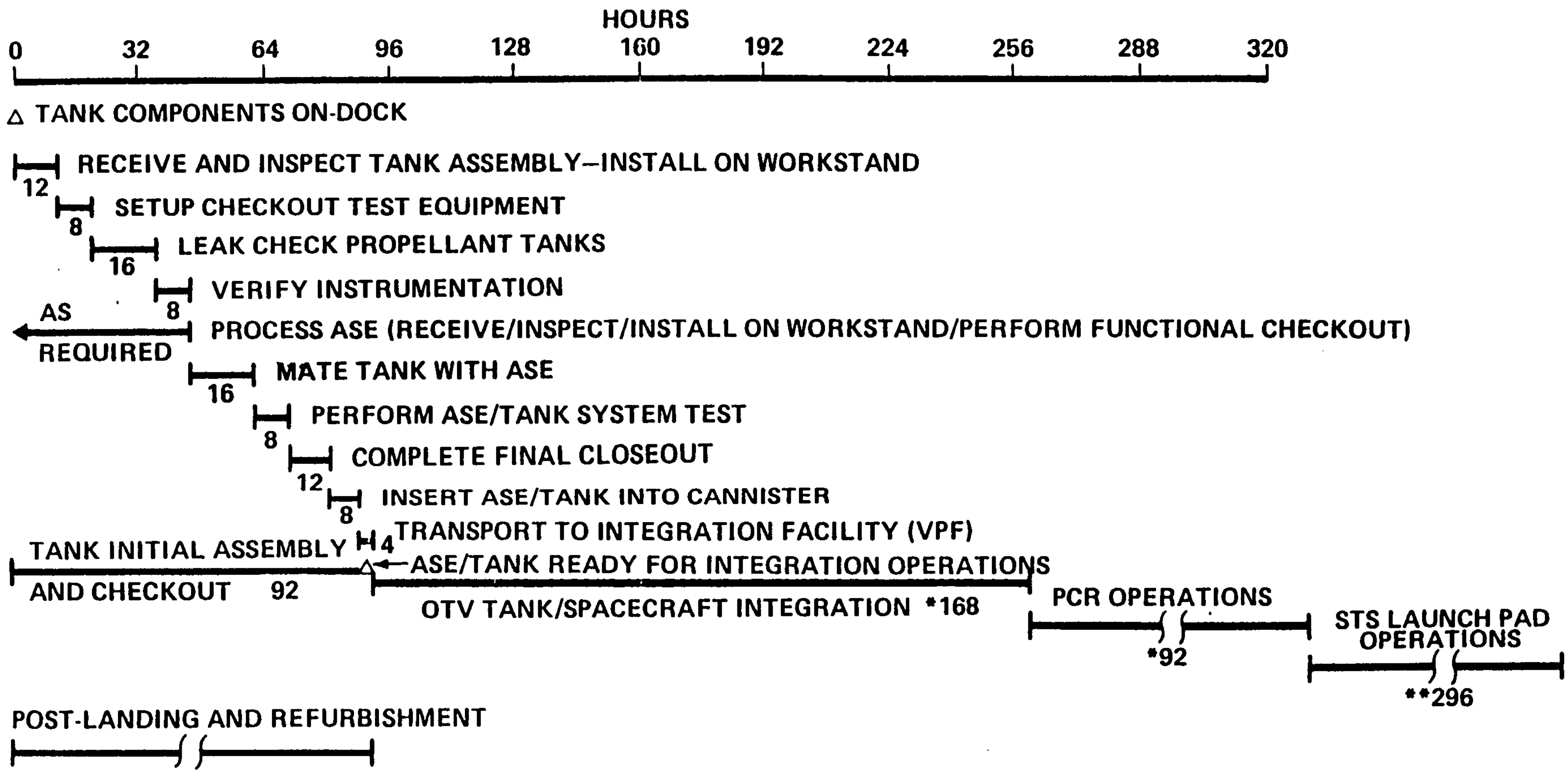
In this scenario the tank set is merely transported to space on the same STS flight as the Spacecraft. This approach requires mating of the OTV, expendable tank set and spacecraft in space.

OTV Only, Spacecraft Only, Expendable Tank Set Or Reusable Tank Module

In this scenario, it is assumed that any two elements exceed the capability of the STS and thus all must be delivered to LEO separately, and then assembled to form the final configuration.

2.1.4 GBOTV Ground Processing Summary

Table 2.1.4-1 summarizes the manyears/flight required to process the various GBOTV, auxiliary tank and spacecraft combinations on the ground. In order to facilitate a comparison of the total processing effort required to get all three components into space, the processing of the spacecraft was arbitrarily assigned 11.0 manyears/flight. The processing of an OTV integrated with a spacecraft was assumed as the baseline with respect to ASE and GSE required.



*GBOTV ANALYSIS

**STAR 27, FIGURE 8, LEVEL III STS TURNAROUND ASSESSMENT

Figure 2.1.3-2 Reusable Auxiliary Tank Ground Operations

OTV-614

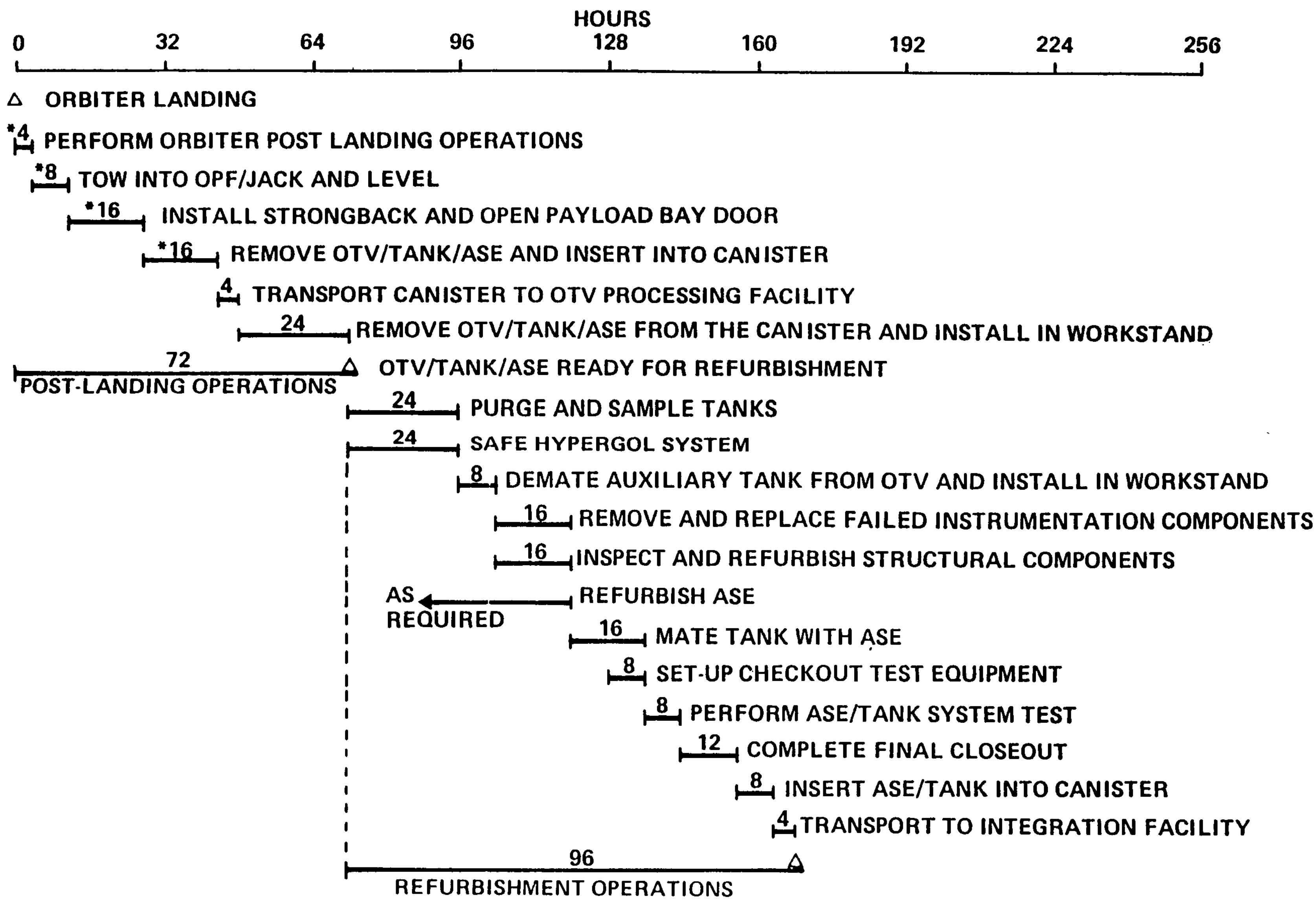
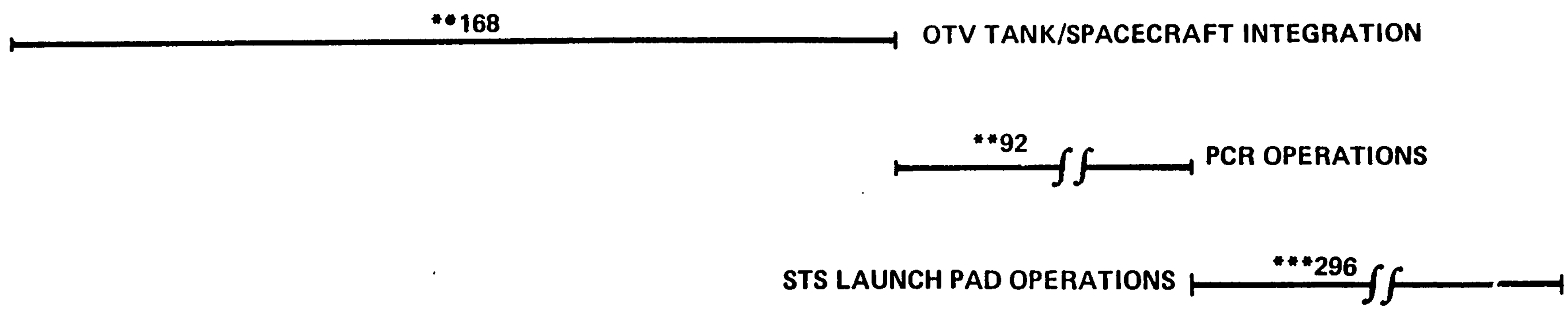


Figure 2.1.3-3 Reusable Auxiliary Tank Turnaround Timeline

OTV-628



NOTES:

1. TIMELINE FROM START OF SPACECRAFT INTEGRATION TO LAUNCH IS IDENTICAL TO GBOTV TIMELINE WHEN TANK MODULE IS MATED TO A SPACECRAFT.
2. ASE RETURNS TO EARTH ON THE SAME STS FLIGHT AND IS REFURBISHED.
3. TANK MODULE RETURNS TO EARTH AS PART OF THE OTV ON A SUBSEQUENT STS FLIGHT AND IS REFURBISHED.

*VSTAR 10, LEVEL III ASSESSED TIMELINE

**GBOTV ANALYSIS

***STAR 27, FIGURE 8, LEVEL III STS TURNAROUND ASSESSMENT

Figure 2.1.3-3 Reusable Auxiliary Tank Turnaround Timeline (Continued)

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Table 2.1.3-2 Ground Based OTV Reusable Auxiliary Tank Ground Processing Effort

MAJOR ACTIVITY	WORK SCHEDULE	NUMBER OF SHIFTS	TIMELINE HOURS	CALENDAR WEEKS PER FLIGHT
INITIAL ASSEMBLY AND CHECKOUT	5 x 8	2	92	1.15
← TURNAROUND →				
POST LANDING OPERATIONS	7 x 12	2	72	0.43**
REFURBISHMENT OPERATIONS	5 x 8	2	96	1.20
OTV TANK/SPACECRAFT INTEGRATION	5 x 8	2	168 ***	2.10 ***
PAYLOAD CHANGEOUT ROOM OPERATIONS	5 x 8	2	92 ***	1.15 ***
STS LAUNCH PAD OPERATIONS	7 x 12	2	296	1.8*
TURNAROUND	---	---	TOTAL	6.83

*EQUIVALENT 5 x 8 TIME EQUALS 4.77 CALENDAR WEEKS
**EQUIVALENT 5 x 8 TIME EQUALS 1.14 CALENDAR WEEKS
***ASSUMES INTEGRATION WITH A SPACECRAFT.

Table 2.1.4-1. GBOTV Ground Processing Summary

CONFIGURATION	RELATIVE PROCESSING EFFORT MANYEARS/FLIGHT*	TURNAROUND TIMELINE WEEKS/FLIGHT*	ASE	GSE	COMMENTS
OTV PLUS SPACECRAFT	10.5	8	ONE UNIT BASELINE	BASELINE	ONE STS FLIGHT
OTV ONLY, SPACECRAFT ONLY	8.5 + 11.0 = 19.5	8 + 8	• SPACECRAFT • OTV	SPACECRAFT SIMULATOR, OTV SIMULATOR	TWO STS FLIGHTS
OTV/SPACECRAFT, EXPENDABLE TANK SET	10.5 + 1.6 = 12.1	10 + 4	• TANK SET • OTV	BASELINE	TWO STS FLIGHTS
OTV, REUSABLE TANK MODULE/SPACECRAFT	8.5 + 2.4 = 10.9	8 + 7	• TANK MODULE/ SPACECRAFT • OTV	SPACECRAFT SIMULATOR, OTV SIMULATOR	TWO STS FLIGHTS
OTV, SPACECRAFT PLUS EXPENDABLE TANK SET	8.5 + 1.6 + 11.0 = 21.1	8 + 8	• TANK SET • SPACECRAFT • OTV	SPACECRAFT SIMULATOR, OTV SIMULATOR	TWO STS FLIGHTS
OTV, SPACECRAFT, EXPENDABLE TANK SET	8.5 + 1.6 + 11.0 = 21.1	8 + 8 + 4	• TANK SET • SPACECRAFT • OTV	SPACECRAFT SIMULATOR, OTV SIMULATOR	THREE STS FLIGHTS
OTV, SPACECRAFT, REUSABLE TANK MODULE	8.5 + 2.4 + 11.0 = 21.9	8 + 8 + 7	• TANK MODULE • SPACECRAFT • OTV	SPACECRAFT SIMULATOR, OTV SIMULATOR	THREE STS FLIGHTS

*Spacecraft only processing arbitrarily assessed at 11.0 manyears and 8 weeks per flight.

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As the configurations depart from the baseline the total manyears/flight, turnaround timeline, number of STS flights and ASE/GSE deltas increase. The weeks to process the flights (turnaround timeline) may occur in parallel depending on integration and launch pad facilities availability.

2.1.5 GBOTV On-Orbit Processing

On-Orbit assembly associated with the GBOTV was analyzed for each of the combinations specified in section 2.1.3. However, because the system level trade selected the reusable auxiliary tank options, only the results of that concept are discussed.

The on-orbit assembly plan presupposes a Space Station with the appropriate accommodations. An alternative is to orbit the initial components(s), rendezvous subsequent STS flight(s) with the orbiting components and mate the elements of the GBOTV at the Orbiter. This scenario was not analyzed.

2.1.5.1 Space Station Operations

Figure 2.1.5-1 depicts a Space Station operational timeline to mate an OTV with a Reusable Auxiliary Propellant Tank Spacecraft, count down and release. The GBOTV is transported in the second STS flight so as to minimize cryogenic fuel boiloff. The APT/Spacecraft is stored at the Space Station until the GBOTV arrives.

The timeline, while typical in the general sequencing of events, is the shortest of scenarios considered. A mating of the expendable tank set to the OTV involves two interfaces (structural, mechanical, and electrical) versus the one for the reusable APT. Scenarios which involve 3 STS flights and subsequent matings of OTV-to-Auxiliary Tanks-to-Spacecraft result in a considerably longer timeline. The timeline assumes all premate interface verifications were performed during ground operations and are not required at the Space Station.

2.1.5.2 GBOTV On-Orbit Processing Summary

The processing effort summary for several GBOTV combinations is shown in Table 2.1.5-1. These data are based on the following:

a. One hour EVA to acquire and secure any component,

b. Two hours of preparation and cleanup for any EVA shift,

c. 4.5 hours of EVA serial time to mate the OTV to the Expendable Tank Set,

d. 2.2 hours of EVA serial time to mate either the OTV to the spacecraft, the OTV to the Reusable Tank Module or the Reusable Tank Module to the Spacecraft, and

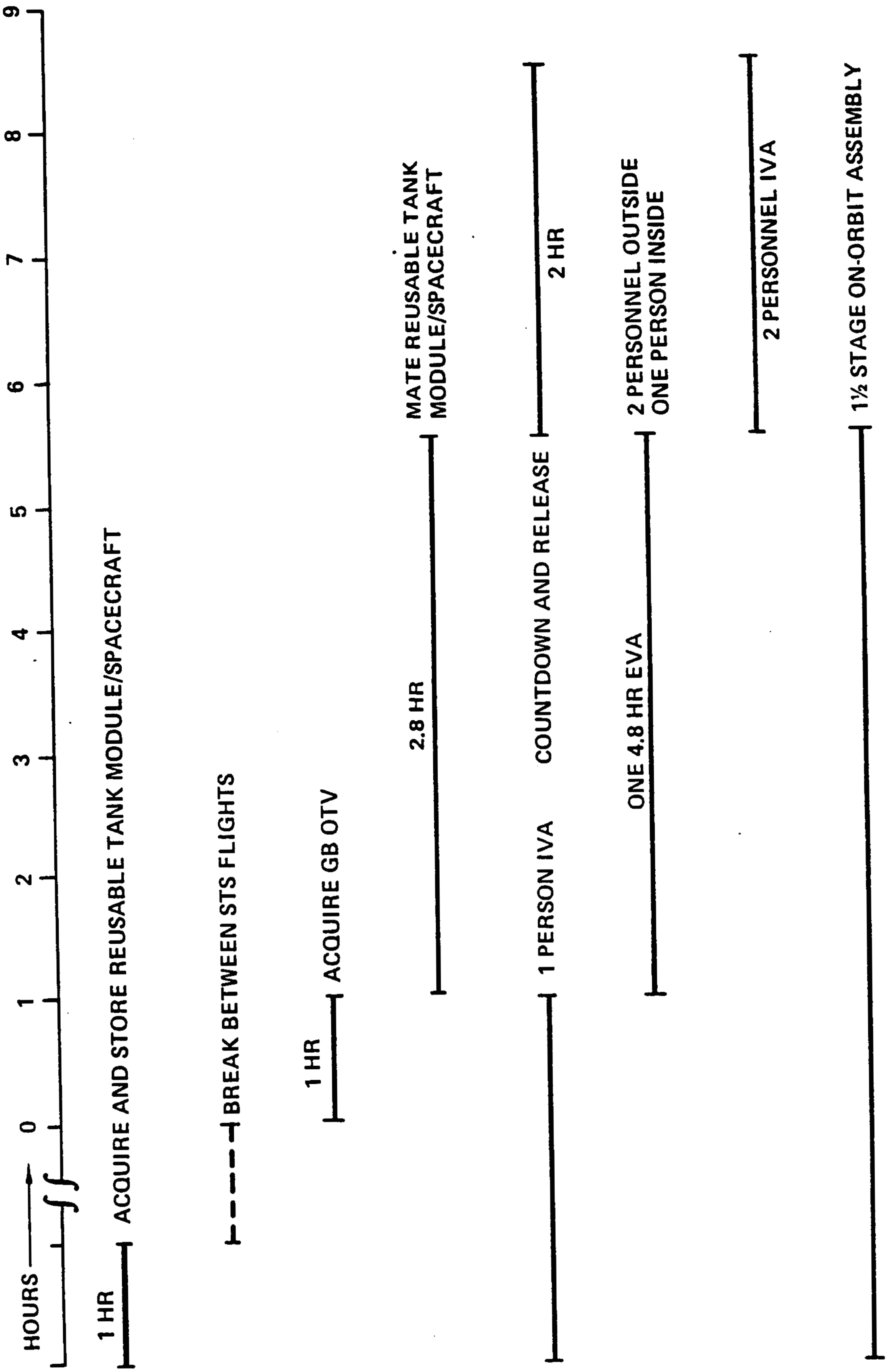

Figure 2.1.5-1 GBOTV/Space Station Operations

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Table 2.1.5-1 Key Elements of 1 1/2 Stage on Orbit Assembly Plan GBOTV

- PERFORM PREMATE INTERFACE VERIFICATION DURING GROUND PROCESSING:
  - OTV-TO-SPACECRAFT
  - OTV-TO-AUXILIARY TANK(S)
- MULTIPLE STS FLIGHTS (MAXIMUM OF THREE). CRYOGENIC FUEL BOILOFF CONSIDERATIONS DICTATE OTV TO BE IN LAST STS FLIGHT
- SPACE STATION ACCOMMODATIONS:
  - STORAGE/SERVICING BAY(S)
  - PAYLOAD MATING STAND

ASSEMBLY OPTIONS	CREWTIME (MANHOURS)	
	EVA	IVA
a. OTV-TO-SPACECRAFT	8.4	6.2
b. OTV/SPACECRAFT-TO-EXPENDABLE TANKS	13.0	8.5
c. OTV-TO-REUSABLE TANK MODULE/SPACECRAFT	9.6	6.8
d. OTV/REUSABLE TANK MODULE-TO-SPACECRAFT	8.4	6.2
e. OTV-TO-SPACECRAFT-TO-EXPENDABLE TANKS	17.4	11.4
f. OTV-TO-REUSABLE TANK MODULE-TO-SPACE-CRAFT	14.0	10.0

GVOTV ON-ORBIT ASSEMBLY OPTIONS TIMELINE SUMMARY

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e. 2 personnel outside plus 1 person inside during any EVA shift.

f. The crew times indicated do not include the 4 hours of EVA crewtime involved with countdown and release.

An example of using the above data to establish the man-hours for the tasks indicated in Table 2.1.5-1 is as follows:

b. OTV/Spacecraft to expendable tasks

4.5	hrs of serial time
x 2	people performing the EVA
= 9	EVA hours
	plus 2 hrs/person for prep and cleanup
= 4	hours
	Total = 13 hours of EVA activity

2.2 SPACE BASED ORBITAL TRANSFER VEHICLE (SBOTV) PROCESSING

The Space Based Orbital Transfer Vehicle (SBOTV) concept includes an OTV which is launched empty and is subsequently serviced at a space station. Propellant for the OTV is delivered by a tanker. This section discusses the ground and orbital processing operations associated with these elements including those related to payload and STS integration.

The top-level SBOTV operational functional flow is shown in Figure 2.2-1. The SBOTV operational flow interfaces with and is influenced by the operational flows of the STS and Space Station. It envisions a SBOTV maintained at the Space Station and a SBOTV Tanker which transports propellant to the Space Station. The SBOTV may require assembly at the Space Station (configuration dependant). Characteristics of the three SBOTV configurations analyzed - Ballute Brake, Lifting Brake and Shaped Brake are shown in Figure 2.2-2. The Lifting Brake and shaped Brake size is such that they must be disassembled in order to be delivered by the STS Orbiter and then reassembled on-orbit. A Lifting Brake configuration compatible with an Aft Cargo Carrier (ACC) is also an OTV possibility, however that configuration was not a subject of this analysis.

Operations associated with the SBOTV Tanker at the Space Station (Function 6.0, Offload SBOTV Tanker) are described in section 3.0 of this book.

2.2.1 Assumptions/Guidelines/Derived Requirements

2.2.1.1 Ground Processing

The following assumptions, guidelines and derived requirements are applicable:

a. The processing effort (manyears/flight) necessary to assemble, checkout and integrate a ballute configurated SBOTV is comparable to that required to initially assemble, checkout and integrated the GBOTV.

b. Because the primary thrust of the analysis is to determine comparative values versus absolutes, a disassembly and "packaging" of an OTV is considered equivalent to an assembly and checkout; an integration with the Orbiter is considered equal regardless of the "package" being integrated; and the STS Launch support effort is considered equal for any STS launch.

NOTE: MISSING FUNCTION NUMBERS 3.0, 4.0, 7.0 AND 10.0 RELATE TO GBOTV FUNCTIONS

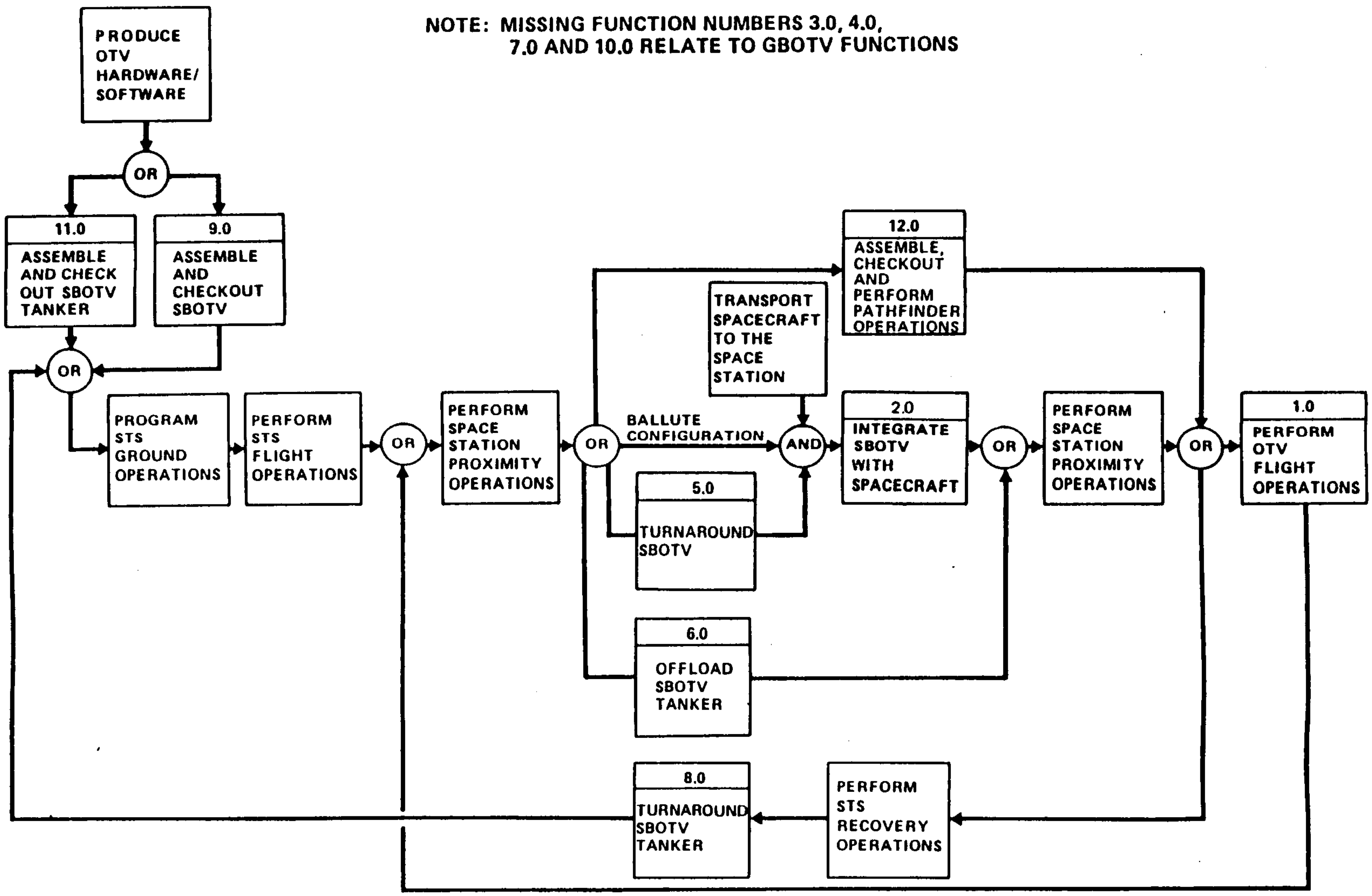
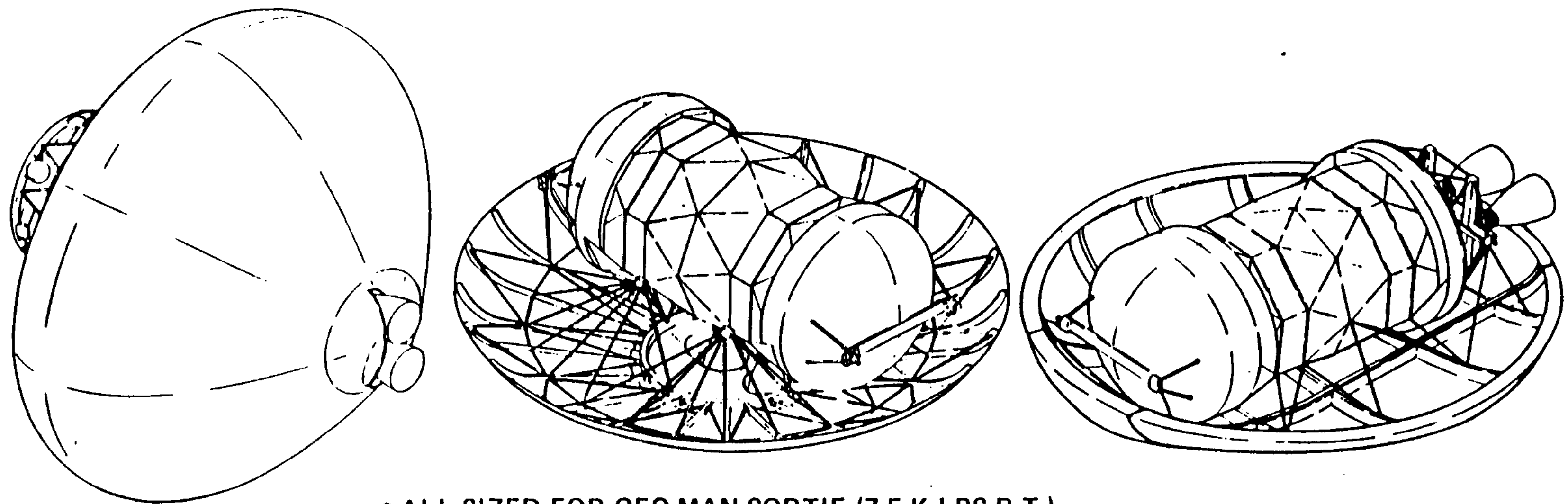


Figure 2.2-1 Top-Level SBOTV Operational Functional Flow

OTV-626



• ALL SIZED FOR GEO MAN SORTIE (7.5 K LBS R.T.)

	BALLUTE BRAKE	LIFTING BRAKE	SHAPED BRAKE
• AEROMANEUVER FEATURES	TDR = 1.5 B/W = 1500°F	L/D = 0.117	L/D = 0.234
• INITIAL ON-ORBIT ASSY.	NO	YES	YES
• VEHICLE SIZE (FT)	14.5 x 35.7 BALLUTE 50 FT. DIA.	42 DIA.	44 x 36
• BRAKE REPLACEMENT FREQ. (FLTS)	BALLUTE (1) HEAT SHIELD (20)	TPS FABRIC (5) HEAT SHIELD (20)	HEAT SHIELD (20)
• DRY WEIGHT (LBS) (BRAKE WT.)	9189 (2712)	9947 (3276)	10314 (3608)
• PROP. WT. (LBS)	63,890	69,681	71,020

Figure 2.2-2 SBOTV Configurations

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2.2.1.2 Space Station Processing

The following assumptions, guidelines and derived requirements are applicable to OTV processing operations occurring at the Space Station:

a. The OTV must be verified "safe" prior to installation in the hangar. This safing is accomplished by mating the OTV to the fuel umbilical, defueling hypergol tanks, purging the fuel cell and transferring data from the vehicle.

b. The average speed that the MRMS moves the loaded OTV or OTV/spacecraft combination is 0.06 ft/sec. (This corresponds to the Shuttle RMS vernier rate of 0.061 ft/sec and is the speed the OTV was moving when it was grabbed by the MRMS. The average speed that the MRMS moves an empty OTV is 0.1 ft/sec (Shuttle RMS coarse rate when loaded).

c. The RMS, or any other moving device, is able to start and stop the OTV safely, reacting to the momentums involved in the movements. Translation of the OTV is done remotely with RMS, requiring one man IVA to operate/monitor the equipment.

d. The hangar Space Station-to-OTV interface includes the structural support, electrical power and communication lines. There may also be plumbing connections depending on purge requirements. This interface is made remotely and automatically when the OTV is secured in the hangar. The verification of the interface is in the form of a functional check or merely a copper path verification if the functional check is not required.

e. Visual inspection of the OTV is done remotely, automatically and systematically so as to keep a record of the condition for trend analysis. The visual inspection is performed with a human monitor with the results of the inspection inputted to a computer for comparison. Only anomalies and their location need further human investigation. This may require external markings (stations) on the vehicle for reference so that a human investigator can readily locate the anomaly.

2.2.1.3 Spacecraft Integration and Release

a. Checkouts are accomplished automatically with only "No-Go" indications analyzed by operators. For purposes of timeline there are no "No-Gos". The timeline for checkouts indicates time to load the software, initiate the test sequence and operator verification that the test did run successfully.

b. Spacecraft unique operations (spacecraft subsystem checkouts, deployments, etc.) are a subject of a different analysis.

c. The spacecraft-to-OTV interface is completely automated with EVA required only for monitoring, visual confirmation/inspection and removal of support equipment after the interface verification testing has been completed.

d. Spacecraft and OTV End-to-End Testing (testing with all of the Space Station and Ground Station control and monitoring facilities in the loop) may be accomplished during the Spacecraft-to-OTV Interface Verification Test. (It is highly unlikely that it can be accomplished in the 0.5 hour allocated unless ground stations, Payload Operations Control Centers, etc. are verified as operational and ready for the test prior to the test.)

e. The Launch Readiness Review is a confirmation by all parties that the automatic test did run and that there were no "No-Gos".

f. The Final Launch Readiness Check is a completely automatic Launch Readiness Review and provides a final verification that all systems (ground, Space Station, spacecraft and OTV) are ready for launch. Human intervention with automatic test sequence will occur only should a No-Go occur.

g. A premate interface verification is required prior to OTV-to-spacecraft mate. This verification will assure successful mechanical and functional mating of the spacecraft and OTV.

2.2.2 SBOTV Ground Processing

The first SBOTV processing operation analyzed was that of the initial assembly and checkout prior to transportation to the Space Station. Figure 2.2.2-1 is a detailed functional flow of the assembly and checkout function. The discriminator between configurations is the requirement to disassemble and package the Lifting Brake and Shaped Brake configurations into orbiter compatible packages (Functions 9.5 and 9.6).

Table 2.2.2-1 displays relative ground processing effort in manyears per flight for the SBOTV. The analysis uses the organization and "headcount" methodology developed for the GBOTV. The processing effort of any of the three configurations was considered equal to that for the GBOTV for the applicable general task; a disassembly and packaging task was considered equal to an assembly and checkout task; and an integration with the Orbiter was considered equal regardless of the "package" being integrated. Detailed assembly, checkout, disassembly and packaging timelines with detailed crew requirements were not part of the analysis performed.

The SBOTV ballute configuration, if integrated with a spacecraft on the ground, requires the same processing effort as the GBOTV initial flight. With no spacecraft integration, the 2.10 weeks of OTV/Spacecraft Integration are deleted.

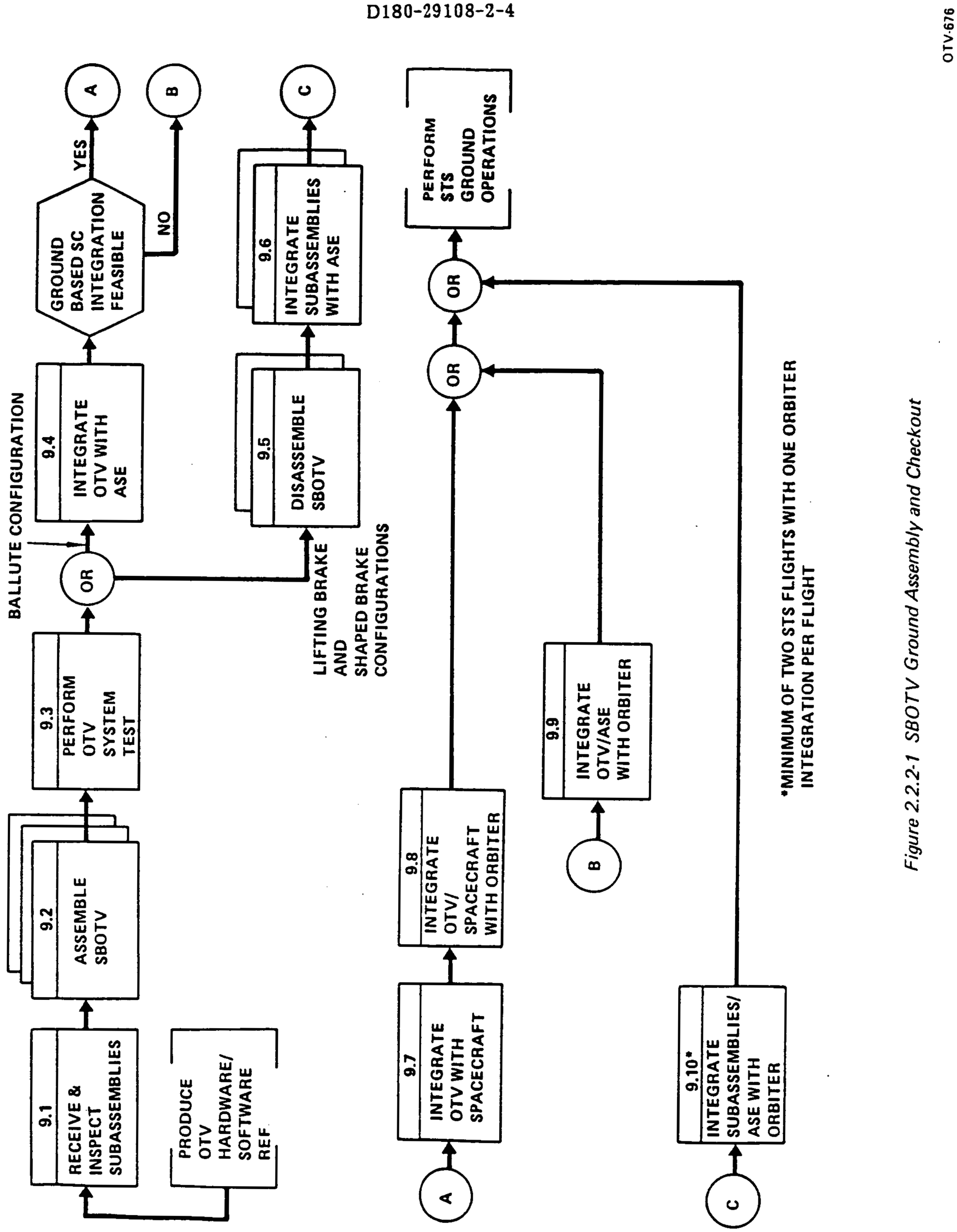

Figure 2.2.2-1 SBOTV Ground Assembly and Checkout

Table 2.2.2-1 Ground Processing Comparison SBOTV

CONFIGURATION	UNIQUE FEATURES	PROCESSING EFFORT (MANYEARS/FLIGHT)
BALLUTE	• FULLY ASSEMBLED CONFIGURATION IS COMPATIBLE WITH THE ORBITER BAY • GROUND-BASED SPACECRAFT INTEGRATION IS POSSIBLE. DEPENDENT ON SPACECRAFT SIZE AND WEIGHT PLUS MISSION PROPELLANT REQUIREMENTS • PROCESSING EFFORT COMPARABLE TO GBOTV.	.92 (2.25 + 2.10 + 1.15 + 4.77) = [1] 9.4 (WITH SPACECRAFT INTEGRATION) .92 (2.25 + 1.15 + 4.77) = 7.5 (WITH NO SPACECRAFT INTEGRATION)
LIFTING BRAKE	• DISSASSEMBLY INTO FOUR SUBASSEMBLIES: 1. CENTER CORE 2. ENGINES 3. BRAKE STRUCTURE 4. BRAKE TPS • ASE/PACKAGING OF SUBASSEMBLIES TENDS TO BE UNIQUE	.92 (2.25 + 1.15 + 4.77) 2 = 15.0 (TWO STS PROCESSINGS, A DISASSEMBLY AND TWO PACKAGINGS)
SHAPED BRAKE	• DISSASSEMBLY INTO AT LEAST FOUR SUBASSEMBLIES 1. CENTER CORE 2. SHAPED BRAKE (3 SEGMENTS) • ASE/PACKAGING OF SHAPED BRAKE TENDS TO BE UNIQUE BECAUSE OF SHAPES AND THERMAL PROTECTION SYSTEM.	.92 [2 (2.25) + 3 (1.15 + 4.77)] = 20.5 (THREE STS PROCESSINGS, A DISASSEMBLY AND THREE PACKAGINGS)

[1] The terms in the equation relate to the following:
0.92 = man-years per work week
2.25 = weeks to perform OTV initial assembly and checkout
2.10 = weeks to perform OTV/spacecraft integration
1.15 = weeks in payload changeout room
4.77 = weeks at STS launch pad

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The SBOTV Lifting Brake configuration is not compatible with the Orbiter cargo bay. The deployed brake assembly exceeds the 15 foot diameter envelope and needs to be folded. The tank set without engines is compatible. The units which must be transported consist of a tank set, two engines, a folded brake structure, disassembled struts and TPS blanket. The Lifting Brake ground processing involves an assembly and disassembly (2.25 weeks each), two Payload Changeout Room Operations and two STS Launch Pad Operations. The total relative ground processing is two times that for the ballute configuration.

The SBOTV Shaped Brake configuration core module, including engines, is compatible with the Orbiter. The brake is divided into three segments; each less than 15 feet wide and approximately 40 feet long. For this analysis, two STS flights were required to transport the brake segments. Further analysis, coordinated with brake design development, needs to be performed so as to optimize the total brake packaging, transportation and assembly efforts. The Shaped Brake ground processing involves an assembly and disassembly (2.25 weeks each) plus three Payload Changeout Room and STS Launch Pad Operations. The total relative ground processing is approximately 3 times that for the ballute configuration.

2.2.3 Space Assembly, Checkout and Pathfinder Operations

Space Assembly and Checkout. The Lifting Brake and Shaped Brake configurations require assembly and checkout at the Space Station due to their size. The flow is characterized by multiple STS flights, assembly of the vehicle, verification of the vehicle assembly and return of unique ASE to earth. The function is very configuration and vehicle characteristic dependant. Figure 2.2.3-1 indicates the flow for the Shaped Brake assembly and checkout. Checkout in the context of this flow is verification that the vehicle has been properly assembled and is a functioning complete system. The assembly sequence for the Lifting Brake and Shaped Brake are depicted in Figures 2.2.3-2 and -3, respectively.

Key elements of the assembly and checkout plan, tailored to OTV assembly but valid for any space station assembly or mating operation, include:

a. Preassembly and checkout on earth to assure functionality and fit,

b. Minimum number of subassemblies,

c. Minimum number of separate connectors (eliminate electrical and plumbing connections between subassemblies if possible),

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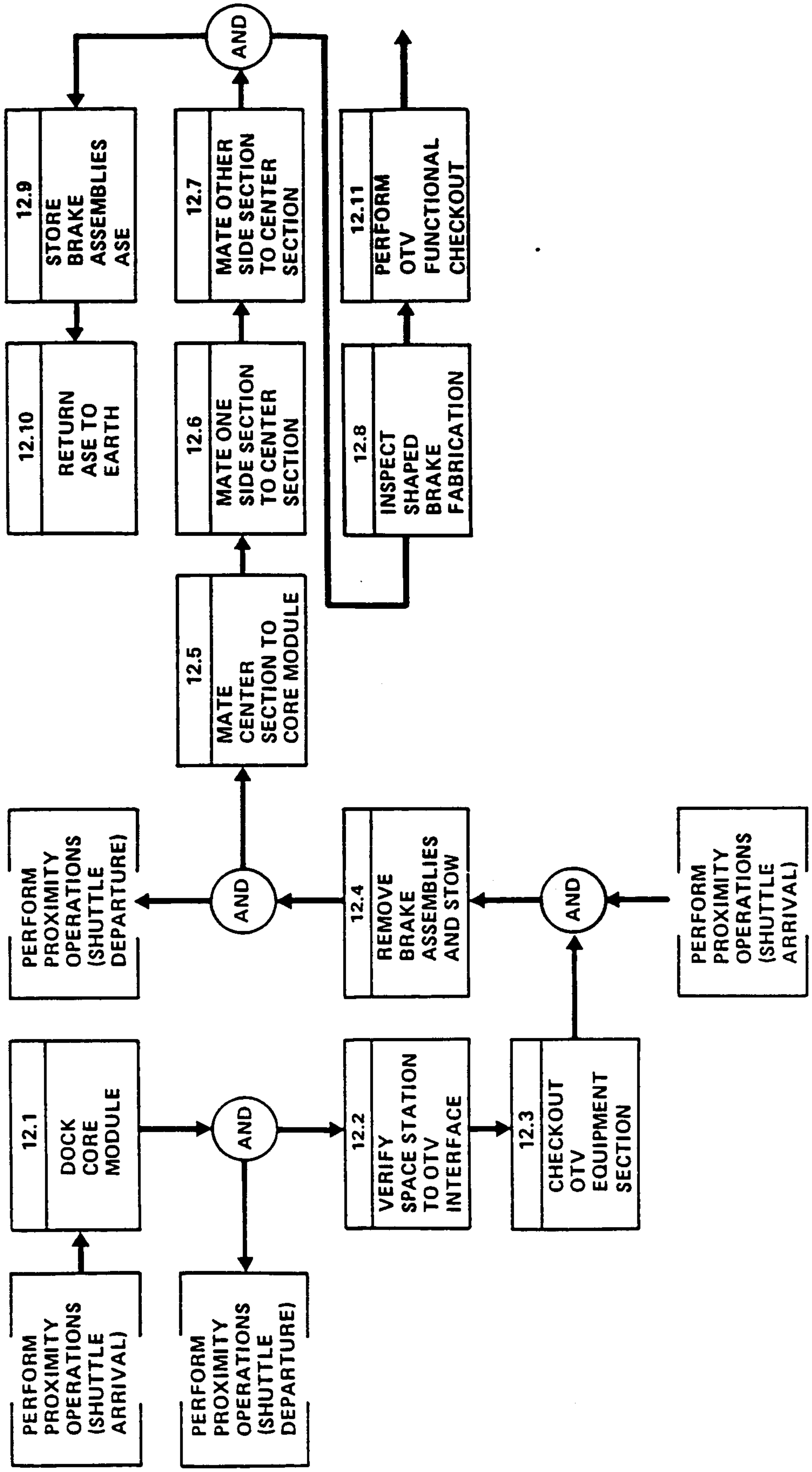

Figure 2.2.3-1 Space Assembly and Checkout SBOTV (Shaped Brake)

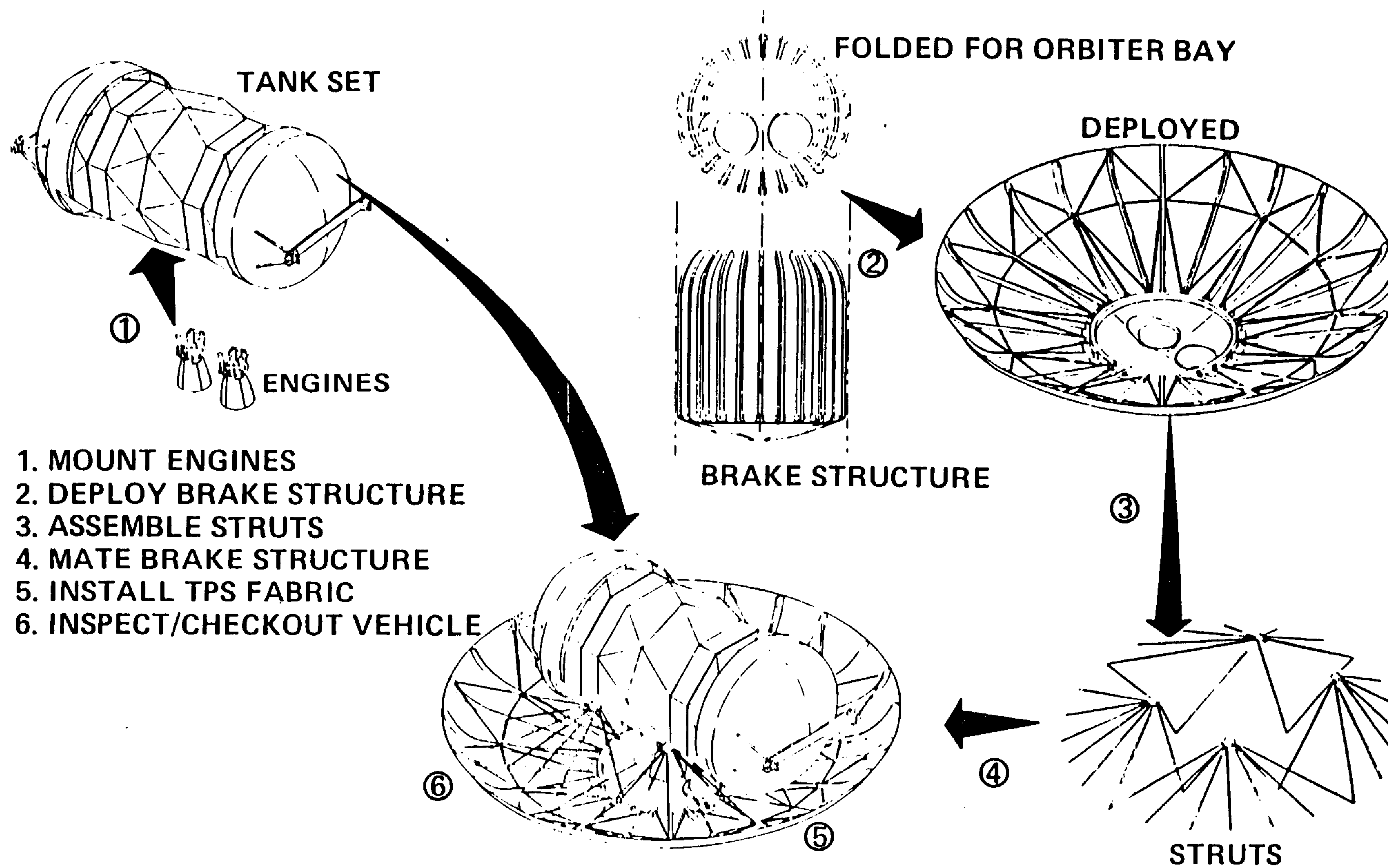

Figure 2.2.3-2 Lifting Brake Assembly Sequence

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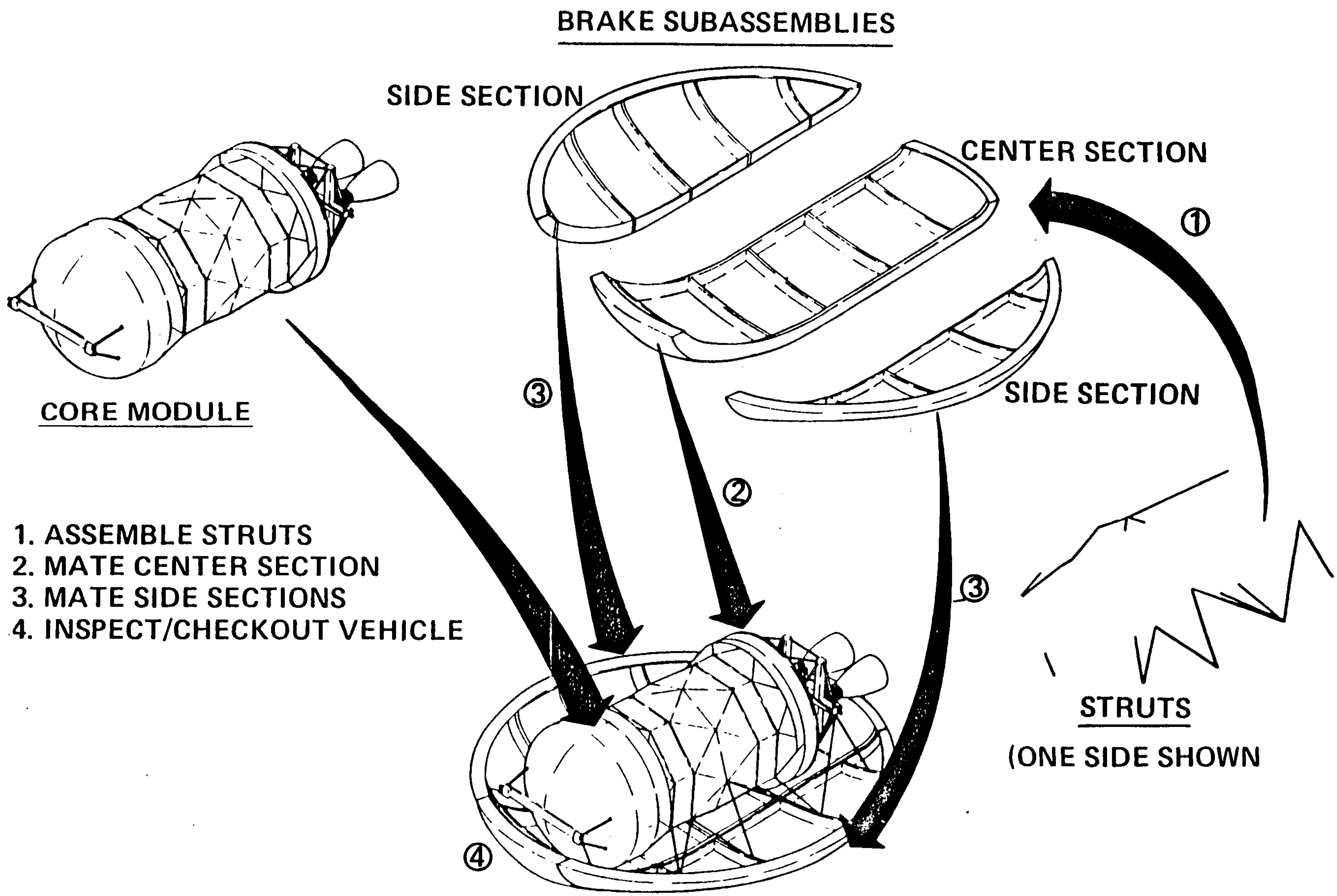

Figure 2.2.3-3 Shaped Brake Assembly Sequence

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d. Installation of grapple fixture or provisions to attach a grapple fixture on each subassembly,
e. Alignment aids, tapered pins or guides, which are integral to the vehicle structure,
f. Automation of repetitive tasks, inspections, joint sealing, etc.,
g. Preplanned assembly tasks to maximize EVA shift productivity, and
h. Use of the first flight vehicle to verify accommodations (eliminate requirement for "Pathfinder", "Trailblazer" vehicles).

Orbital Pathfinder Operations. After the assembly of the initial SBOTV, the vehicle is utilized as a pathfinder to verify the Space Station OTV accommodations. The flow proceeds directly from the assembly flow and includes a vehicle test flight. Concurrent with and part of the verification of the OTV accommodations is the verification of spacecraft accommodations and procedures with a spacecraft simulator. The spacecraft simulator is an instrument package which gathers data to evaluate the vehicle test flight. The Pathfinder operations are not unique to any specific OTV configuration. Figure 2.2.3-4 depicts the functional flow for the pathfinder operations. The operations include a test flight of the newly assembled vehicle and an evaluation prior to declaring the OTV flight worthy. The verification of the Space Station OTV accommodations (Functions 12.15 and 12.16) is a one time activity. Subsequent SBOTV assembly and checkout operations (replacement vehicle or fleet expansion) will be processed through the accommodations to verify vehicle characteristics only.

Assembly, Checkout, Pathfinder Processing Summary, Table 2.2.3-1 lists the functions involved in the assembly, checkout and Pathfinder Operations with the IVA and EVA task times required for the function for each configuration. An "As Required" task completion time indicates a function for which the time to complete was considered indeterminable but equal for each configuration. For example, the Space Station effort involved in Function 12.23, Perform Test Flight Operations, and Function 12.26, Review Flight Data, requires resolution of Space Station on-board autonomy philosophies and the resultant development of procedures for the control of operational functions. It is assumed that whatever the level of on-board autonomy, the Space Station task times will be equal for each configuration.

The total EVA task time is divided by 6 hours/shift to determine the number of EVA shifts. The number of shifts (rounded to the next higher number) is multiplied by 8 hours/shift to give the total EVA time. (This type of adjustment is necessary because the EVA task times do not include any time to exit and enter the pressurized module,

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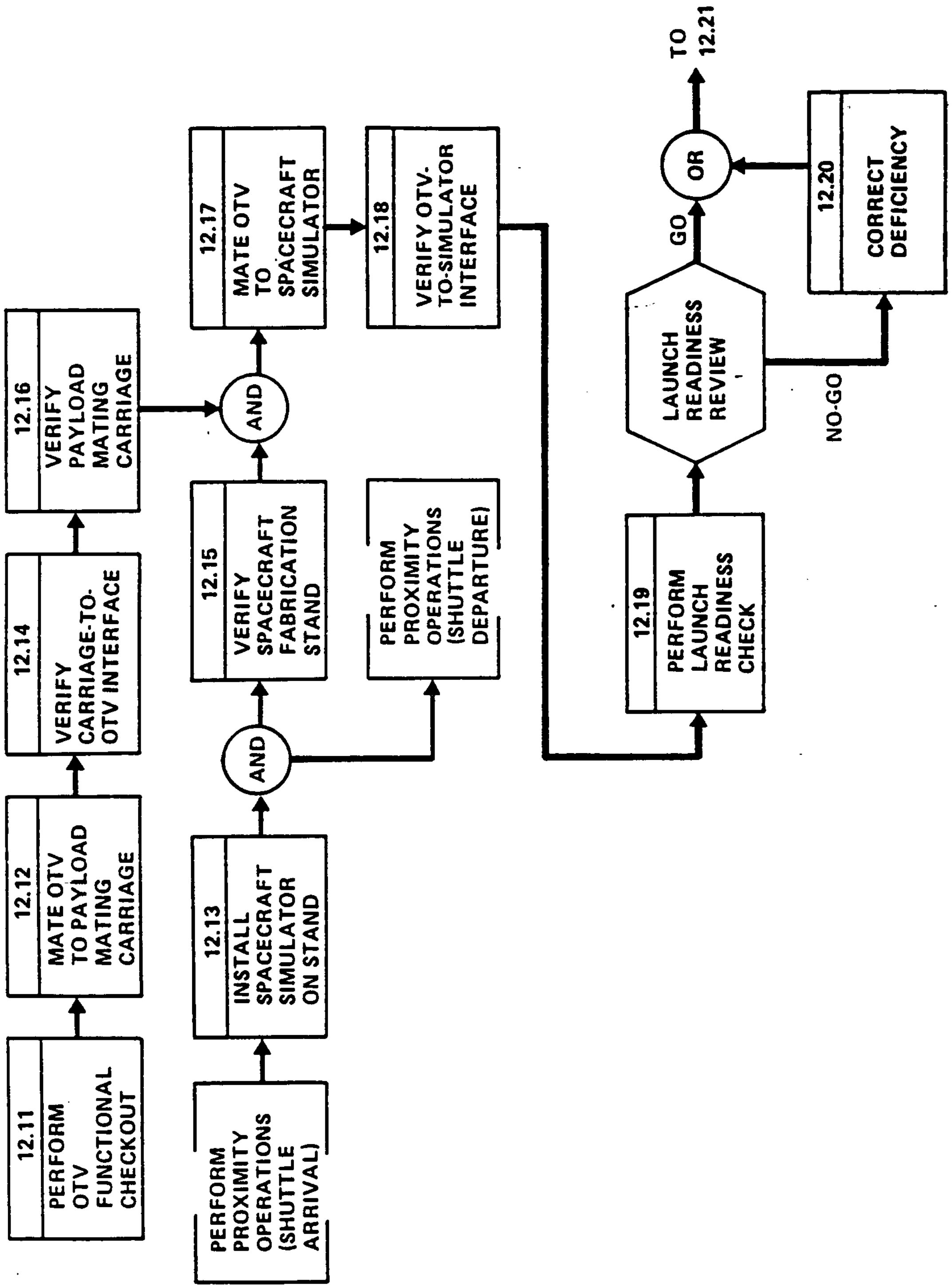

Figure 2.2.3-4 Pathfinder Operations SBOTV

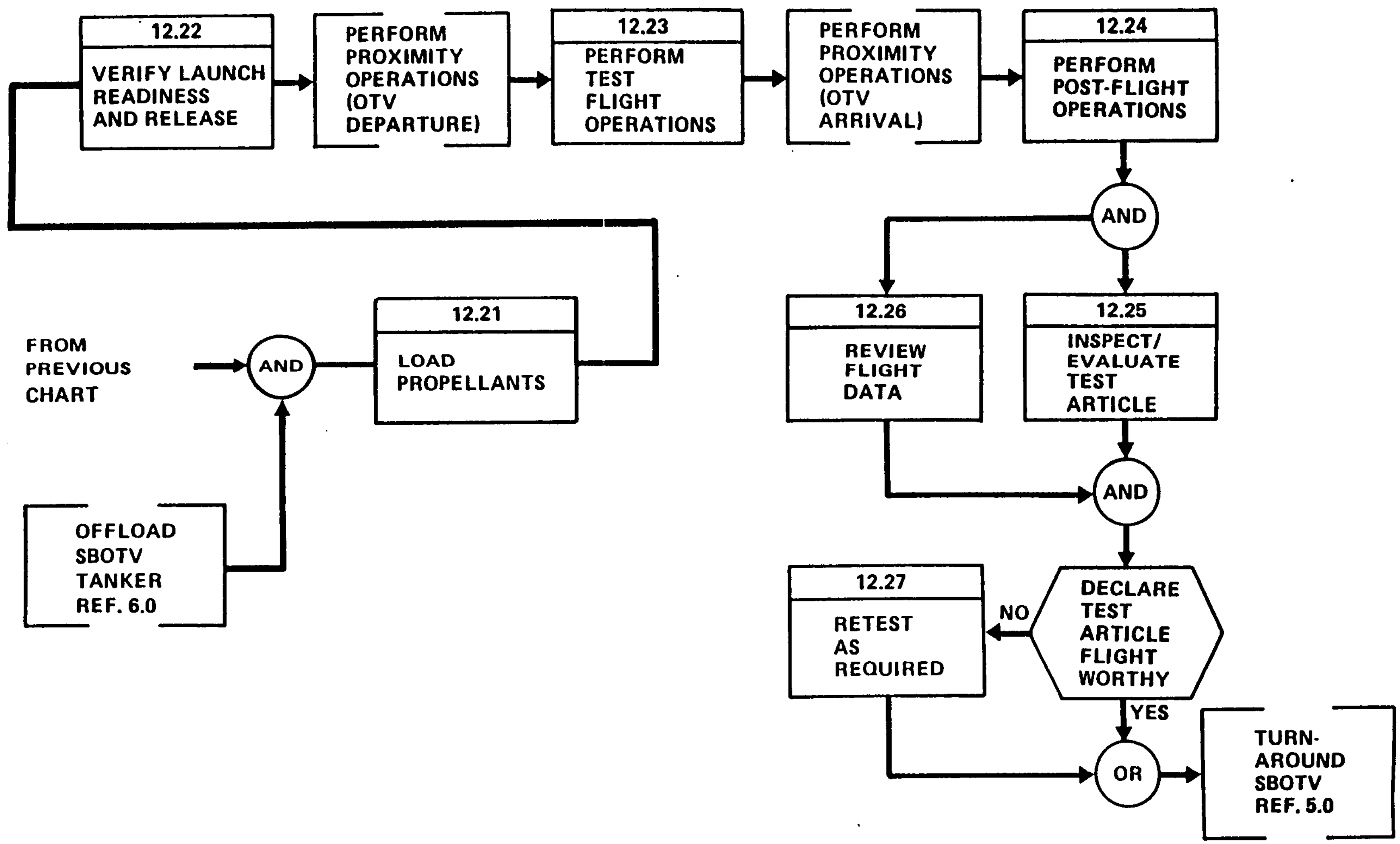

Figure 2.2.3-4 Pathfinder Operations (Continued) SBOTV

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Table 2.2.3-1. Assembly, Checkout and Pathfinder Operations (Sheet 1)

FUNCTION		TASK COMPLETION TIME (HOURS)					
		BALLUTE		LIFTING BRAKE		SHAPED BRAKE	
NUMBER	DESCRIPTION	EVA	IVA	EVA	IVA	EVA	IVA
12.1	DOCK CORE MODULE DOCK TANK SET AND ENGINES DOCK SBOTV		1.5		3.0		1.5
12.2	VERIFY SPACE STATION TO OTV INTERFACE	4.0		4.0		4.0	
12.2A	MATE ENGINES TO TANK SET			10.0			
12.3	CHECKOUT OTV EQUIPMENT SECTION		1.0		1.0		1.0
12.4	REMOVE BRAKE ASSEMBLIES AND DOCK (2 TIMES) REMOVE LIFTING BRAKE COMPONENTS				3.0		3.0
12.5	MATE CENTER SECTION TO CORE MODULE DEPLOY AND MATE BRAKE STRUCTURE			11.0		7.2	
12.6	MATE ONE SIDE SECTION TO CENTER SECTION JOIN TPS FABRIC TO BRAKE STRUCTURE			36.0		9.8	
12.7	MATE OTHER SIDE SECTION TO CENTER SECTION					9.8	
12.8	INSPECT SHAPED BRAKE FABRICATION INSPECT LIFTING BRAKE FABRICATION				12.0	2.0	12.0
12.9	STORE BRAKE ASSEMBLIES ASE			1.0		1.0	
12.10	RETURN ASE TO EARTH				1.0		1.0
12.11	PERFORM OTV FUNCTIONAL CHECKOUT		1.0		1.0		1.0
12.12	MATE OTV TO SPACECRAFT MATING CARRIAGE	2.0		2.0		2.0	

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Table 2.2.3-1. Assembly, Checkout and Pathfinder Operations (Sheet 2)

FUNCTION		TASK COMPLETION TIME (HOURS)					
		BALLUTE		LIFTING BRAKE		SHAPED BRAKE	
NUMBER	DESCRIPTION	EVA	IVA	EVA	IVA	EVA	IVA
12.13	INSTALL SPACECRAFT SIMULATOR ON STAND	2.0		2.0		2.0	
12.14	VERIFY CARRIAGE-TO-OTV INTERFACE	4.0		4.0		4.0	
12.15	VERIFY SPACECRAFT FABRICATION STAND	4.0		4.0		4.0	
12.16	VERIFY PAYLOAD MATING CARRIAGE	4.0		4.0		4.0	
12.17	MATE OTV TO SPACECRAFT SIMULATOR	1.0		1.0		1.0	
12.18	VERIFY OTV-TO-SPACECRAFT INTERFACE	0.5		0.5		0.5	
12.19	PERFORM LAUNCH READINESS CHECK (2 PEOPLE IVA)		4.0		4.0		4.0
12.20	CORRECT DEFFICIENCY	← AS REQUIRED →					
12.21	LOAD PROPELLANTS (2 PEOPLE IVA)		7.0		7.0		7.0
12.22	VERIFY LAUNCH READINESS AND RELEASE (2 PEOPLE IVA)		2.0		2.0		2.0
12.23	PERFORM TEST FLIGHT OPERATIONS	← AS REQUIRED →					
12.24	PERFORM POST FLIGHT OPERATIONS (2 PEOPLE IVA)		4.0		4.0		4.0
12.25	INSPECT/EVALUATE TEST ARTICLE	6.0		6.0		6.0	
12.26	REVIEW FLIGHT DATA	← AS REQUIRED →					
12.27	RETEST AS REQUIRED	← AS REQUIRED →					
	TOTAL TASK TIMES	27.5	20.5	85.5	38.0	57.3	36.5

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any rest times during the EVA work period or any time for task scheduling inefficiencies.) An EVA involves two crew members outside and one inside. Thus the total EVA crewtime is the total EVA multiplied by 2. The IVA crewtime in support of EVA is equal to the total EVA.

The total IVA task time listed does not include the IVA crewtime in support of EVA. Functions 12.19, 12.21, 12.22 and 12.24 require 2 people IVA for 17 hours. Thus; the IVA crewtime is the list IVA task time plus 17 hours plus the total EVA.

The total time for any configuration is the sum of the EVA and IVA task times. Table 2.2.3-2 reflects a summary of the relative processing effort for assembly, checkout and pathfinder operations by the SBOTV configuration. The ballute configuration processing effort essentially represents the pathfinder operations (no orbit assembly). The processing effort indicated for the lifting brake and shaped brake includes the assembly, checkout and pathfinder operations effort. An equivalent earth crewtime based on relative costs for EVA, IVA and earth processing is indicated. This allows summing the EVA and IVA "effort" on a common basis for all configurations and indicates the relative equivalent earth based cost.

2.2.4 Reflight Processing Operations

Reflight of a SBOTV involves turnaround operations which prepare the OTV itself and integration operations dealing with the joint activity involving the OTV and spacecraft and their final preparations prior to flight. A turnaround operations flow applicable to any of the SBOTV configurations is presented in Figure 2.2.4-1. It is based on the "Station Flight Operations" flow presented in Volume IV of this report and the "Turnaround Flow Space Based OTV" defined in Reference 3. It commences when the OTV has been successfully acquired by the Station (part of the "proximity operations") and ends with the OTV checked out and ready for spacecraft mate. The function flow for the final integration activities is shown in Figure 2.2.4-2.

A top level timeline for these operations is presented for a ballute braked OTV in Figure 2.2.4-3 and is typical of those developed for the other configurations. The timeline indicates a "best estimate" of the number of days required to turnaround a SBOTV, integrate it with a spacecraft, refuel and release. It includes an analysis of the flight and inspection data maintenance planning. Spacecraft generated requirements will impact the timeline and are not necessarily included. Discriminators between SBOTV configurations are not reflected.

The timelines for the other configurations include the same functions (except for the installation of a ballute) with adjustments in task duration appropriate to the

Table 2.2.3-2 Assembly and Pathfinder Operations Comparison SBOTV

CONFIGURATION	UNIQUE FEATURES	EVA [2] CREWTIME (MANHOURS)	IVA [3] CREWTIME (MANHOURS)	EQUIVALENT EARTH CREWTIME (MANYEARS) [1]
BALLUTE	• ASSEMBLED ON EARTH • MINIMUM CHECKOUT AND INSPECTION PRIOR TO TEST FLIGHT • ONE SHUTTLE FLIGHT	80 (2x5x8)	77.5 (20.5 + 17.0 + 40.0)	53
LIFTING BRAKE	• TWO SHUTTLE FLIGHTS • ENGINE MATE • BRAKE STRUCTURE MATE • BRAKE FABRIC MATE • INSPECTION	240 (2 x 15 x 8)	175 (38.0 + 17.0 +12 + 120.0)	149
SHAPED BRAKE	• THREE SHUTTLE FLIGHTS • STRUCTURAL MATE (4 PIECES) • INSPECTION	160 (2 x 10 x 8)	133.5 (36.5 + 17.0 + 80.0)	102

[1] COST BASIS: 1 EVA HR = 6 EARTH MAN MONTHS
1 IVA HR = 2 EARTH MAN MONTHS

[2] BASIS: MEN X NUMBER OF SHIFTS X HOURS/SHIFT

[3] BASIS: IVA + 2 MAN EVA + EVA SUPPORT

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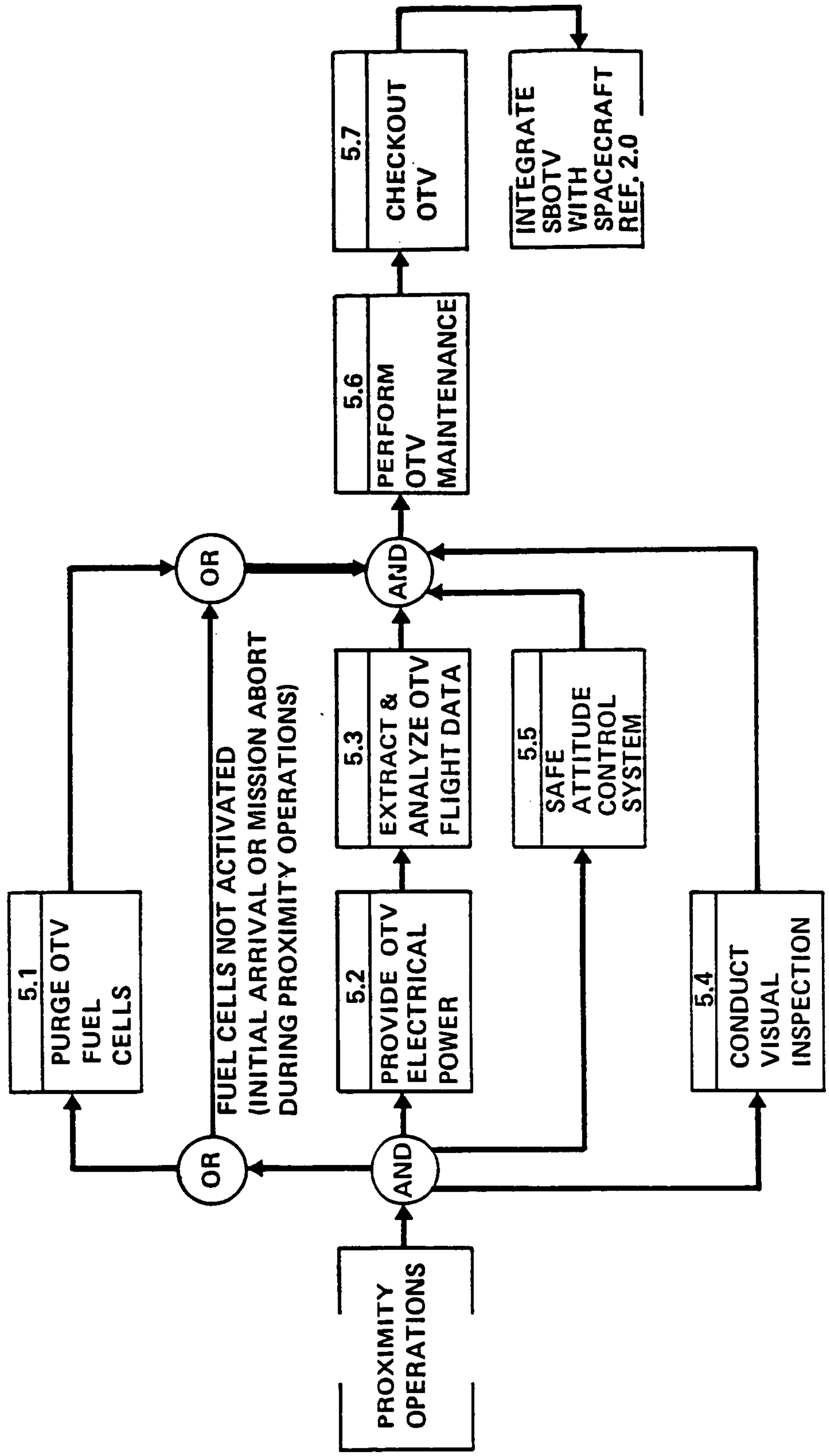

Figure 2.2.4-1 Turnaround Space Based OTV - Function 5.0

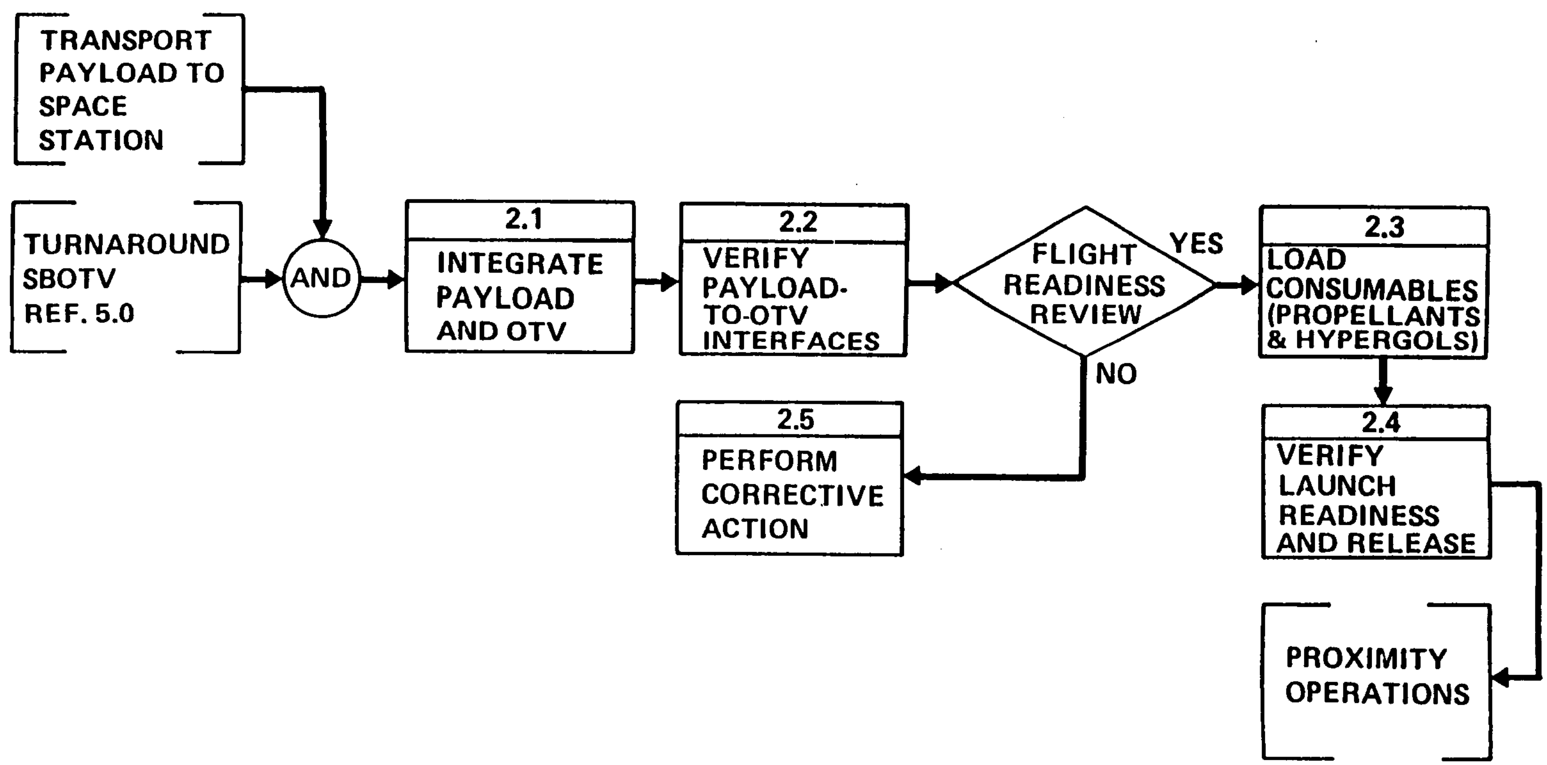

Figure 2.2.4-2 SBOTV Integration Operations - Function 2.0

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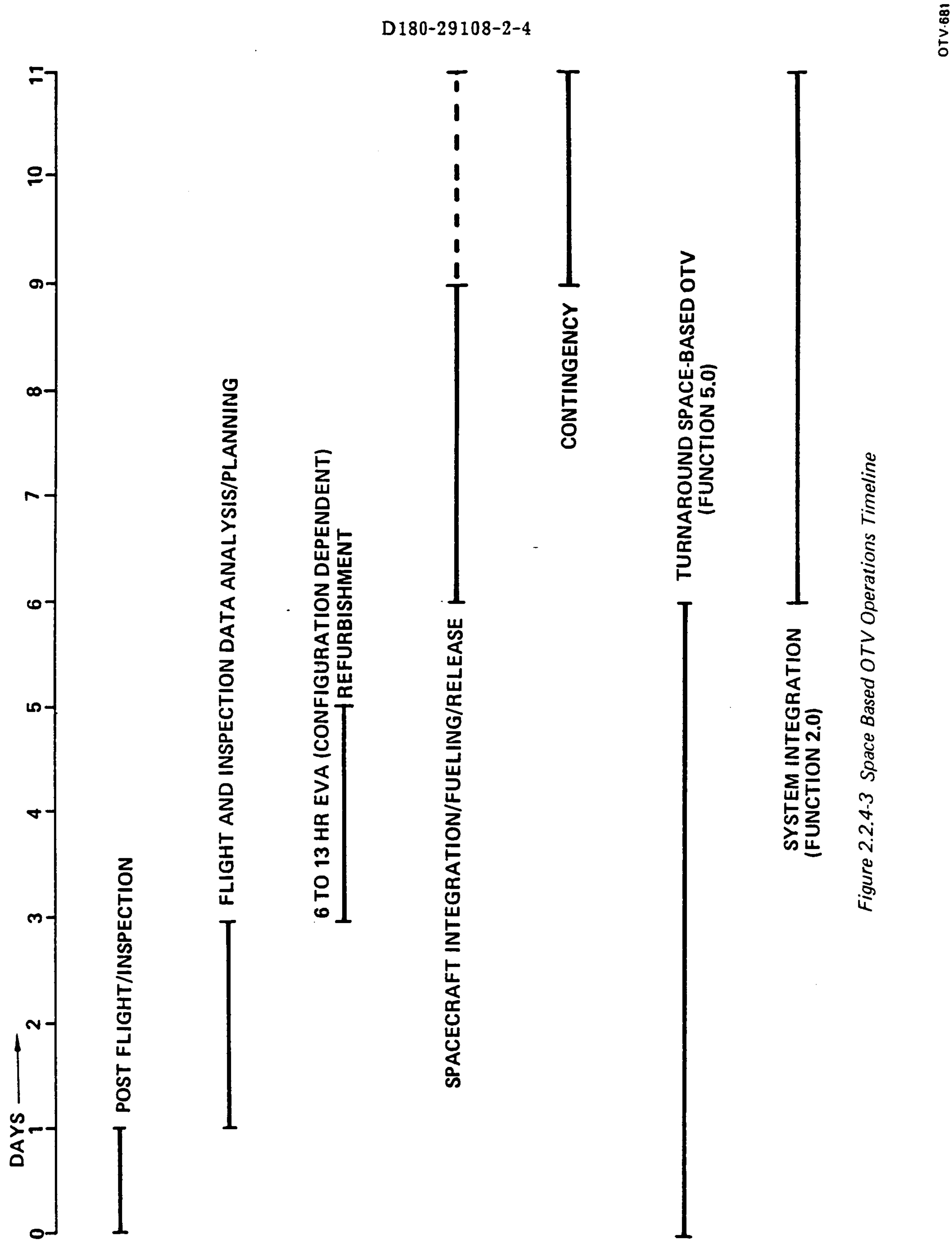


Figure 2.2.4-3 Space Based OTV Operations Timeline

configuration. Checkout of subsystems repaired or maintained is performed as part of the specific repair/maintenance activity. The timeline scenario envisions autonomous vehicle self-check which eliminates a requirement for system level testing. The system checks itself continuously, requiring processing only when the checking indicates a fault requiring corrective action.

The indicated timeline reflects a space processing plan that relies on greatly simplified interfaces between SBOTV subsystem components, the vehicle structure and spacecraft (payloads) to facilitate (and perhaps even allow) maintenance and repair in a space environment. Key elements of a successful space processing plan include:

a. Simplified structural interface(s),
b. Minimal mechanical and electrical connections at interfaces,
c. Autonomous vehicle self-check (Built-In-Test-Equipment, fault analysis and fault isolation),
d. Robotics for repetitive tasks, and
e. Standardized test procedures and documentation methodology.

The "motivation" for simplified interfaces is cost. Based on study groundrules, one manhour of EVA is $48,000 and one hour of IVA is $16,000. (Note that Phase II groundrules raised the EVA cost to $81,000 per hour and $18,000 per hour for IVA). Current "wraparound' costs associated with KSC processing is approximately $96,000 per man year. Based on this data one man hour of EVA equals 6 man months of ground processing cost and one IVA man hour equates to 2 man months of ground cost.

2.2.4.1 Ballute OTV Turnaround

Additional timeline detail regarding the turnaround operations for the ballute OTV is shown in Figure 2.2.4-4. Further information concerning inspection, heat shield removal and replace, main engine remove and replace, and ballute installation is provided in the following paragraphs.

Visual Inspection. The indicated inspection time assumes the use of a robotic manipulator (installed in the hangar). If, a camera is mounted on the manipulator arm, the speed of the movement of the arm averages 0.1 ft/sec (0.1 ft/sec is the maximum tip speed of the Shuttle RMS loaded arm) and the camera records a 1 foot wide strip. The camera is inspecting at a rate of:

$$60 \text{ sec/min} \times 1\text{ft} \times 0.1\text{ft/sec} = 6\text{ft}^2/\text{min}.$$

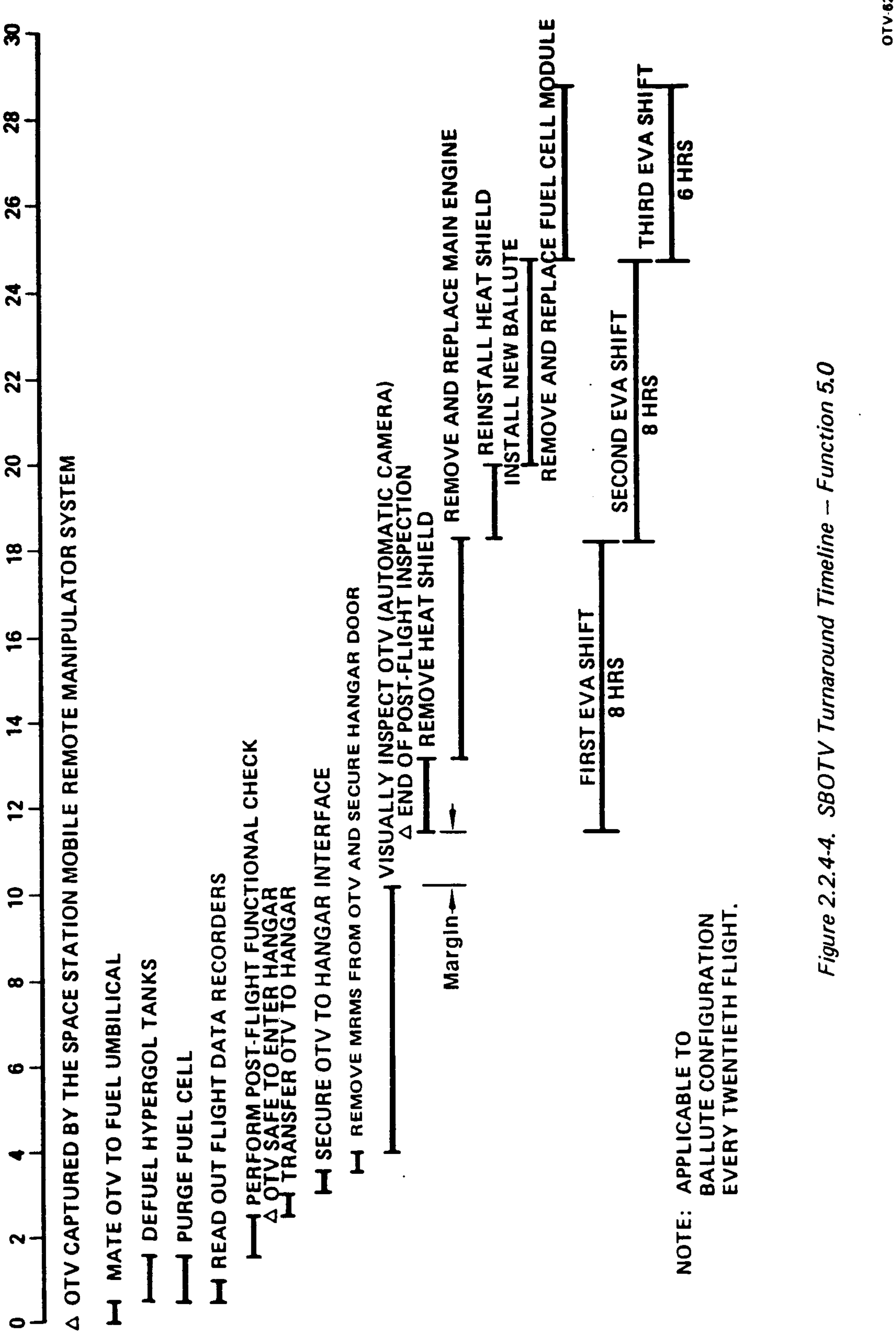


Figure 2.2.4-4. SBOTV Turnaround Timeline – Function 5.0

The ballute configuration can be approximated by a closed 36 ft. long cylinder with a 15 ft diameter. The area to be inspected equals:

$$(3.14)\,(36)15 + (2)\,(3.14)\,(15/2)^2 = 2050\text{ft}^2$$

The time to visually inspect an OTV using a ballute equals:

$$2050\text{ft}^2 \div 6\text{ft}^2/\text{min} = 342 \text{ minutes}$$

The manipulator arm must be capable of obtaining the camera from its storage location and returning it to that location when the inspection task is complete. The storage location is someplace on the inside of the hangar wall. The inspection data can be stored in the camera and transferred for processing after the camera is returned to its storage location. Alternatively, the data could be transferred during the inspection process. Transferring the data simultaneously with inspection requires the least time but may require more hardware. The detailed design will resolve the approach.

In any case, some additional time needs to be allocated for camera acquisition by the manipulator and transport of the camera to and from storage. The additional time is allocated as follows:

Manipulator arm travel to the camera	= 5-10 minutes
Camera acquisition/release	= 1 minute
Transport of camera to/from inspection area	= 5 minutes

Assume 15 minutes are required prior to the start of the inspection to acquire and transport the camera and 6 minutes are required after completion of the inspection to stow the camera. The data is transferred during the inspection process. The total timeline for a vehicle inspection is:

Ballute configurations: $$\frac{15 + 342 + 6}{60} = 6.05 \text{ hours}$$

The inspections require a one man IVA.

Remove and Replace Main Engine. The main engine is normally replaced every 20 flights. The timeline of 5.1 hours to accomplish an engine changeout was extracted from Reference 15. The timeline includes removal, installation, and checkout of an engine assembly and assumes that the appropriate tools, accommodations, and interface designs exist. The indicated time however does not include that associated with removal of the heat shield which is necessary in order to gain access to the engine.

Remove and Replace Heat Shield. The rigid TPS heat shield of the ballute OTV is to be placed every 20 flights (study groundrules) and every time a main engine is replaced.

Table 2.2.4-2 depicts the tasks and task durations necessary to remove and replace a Ballute configuration heat shield. The assumptions applicable to the timeline include:

a. There is a hard point interface inside the engine door(s) which can be accessed from the outside when the doors are open. This interface mates with an aerosell handling tool (see Space Station Accommodations).
b. The RMS is used to position the heat shield. EVA personnel serve as controllers and scanners. They manually guide the heat shield in the vicinity of the OTV and storage pedestal so as to maintain proper clearances.
c. The heat shield is stored on a pedestal which structurally interfaces with the heat shield at the same interface as the OTV.

Ballute Installation. The ballute is replaced after each flight. Table 2.2.4-3 depicts the ballute installation timeline with personnel and tool requirements. Assumptions applicable to the timeline include:

a. There is a ballute handling tool which interfaces with the ballute and a RMS. The RMS is used to transfer the ballute from its shipping container to the rear of the OTV.
b. The OTV has a ballute installation/jettison system which mechanically assists moving the ballute forward. The ballute installation/jettison system also mechanically assists the ballute off the OTV after the aeroassist maneuver.
c. The ballute is attached to the OTV with an upper and low Marmon clamp. There are interfaces between the ballute and OTV to provide (1) gas to the ballute, and (2) signal and power to separate/loosen the super Marmon clamp. The lower Marmon clamp remains with the OTV and does not require a ballute-to-OTV power or signal interface.

2.2.4.2 Lifting Brake OTV Turnaround

The majority of the operations for the Lifting Brake (L/B) OTV are similar to those associated with the ballute OTV. Those that are different in time include visual

TABLE 2.2.4-2 REMOVE AND REPLACE HEAT SHIELD

(REQUIRED ACTION FOR ENGINE CHANGEOUT-BALLUTE CONFIGURATION)

	TASK	Minutes	Hrs + Min
1.	Remove tools and aeroshell handling tool from stores, prepare and checkout mobile robot(s), verify electrical power is off, engine nozzles are retracted and engine door is open.	30	
2.	Disconnect electrical power connector between OTV and heat shield.	5	
3.	Attach aeroshell handling tool to heat shield.	15	
4.	Open Hangar door, position RMS and attach RMS to the aeroshell handling tool (partially parallel-assume 10 minute serial).	10	1 + 00
5.	Release the marmon clamp and secure above heat shield-to-OTV interface. (Secure in three places minimum)	15	
6.	Slide the heat shield rearward with the RMS. (EVA personnel guiding forward portion of the shield structure as required so as to preclude contact with the engine nozzles.)	10	
7.	Move heat shield to storage location and position.	10	
8.	Secure heat shield in storage location with marmon clamp and remove RMS from handling fixtures.	5	1 + 40

Proceed with Engine Changeout

When Engine Changeout is Complete; transfer RMS to heat shield storage location and:

9.	Connect RMS to aeroshell handling tool, remove marmon clamp.	5	
10.	Move new heat shield to rear of OTV. Position heat shield for replacement. Position EVA personnel.	10	
11.	Move heat shield forward with the RMS with EVA personnel guiding the forward portion of the heat shield so as to preclude contact with the engine nozzles. Mate heat shield with OTV structure.	15	

TABLE 2.2.4-2 REMOVE AND REPLACE HEAT SHIELD (CONTINUED)

	TASK	Minutes	Hrs + Min
12	Install marmon clamp and secure.	15	
13.	Disconnect RMS and remove aeroshell handling tool.	15	1 + 00
14.	Connect electrical power connector between OTV and heat shield.	5	
15.	Apply electrical power to OTV. Verify electrical interface. (Cycle door, verify ballute push-off mechanism operation)	10	
16.	Extend engine nozzles, verify clearances, retract engine nozzles, shut down OTV electrical power.	15	
17.	Stow tools, aeroshell handling tool, mobile robot(s) and astronaut foot restraint/control panels(s). Remove RMS from hangar and close hangar door	25	1 + 55

Personnel Requirements:
2 EVA and 1 IVA

Tool Requirements:
1. Aeroshell Handling Tool
2. Mobile Robots(s)
3. Astronaut Foot Restraint/Control Panel
4. Remote Manipulator System (RMS)
5. Miscellaneous hand tools

TABLE 2.2.4-3 BALLUTE INSTALLATION

	TASK	Minutes	Hrs + Min
1.	Remove tools from stores, configure mobile robots and checkout astronaut foot restrain/control panel.	30	
2.	Transfer upper marmon clamp from stores to work area.	10	
3.	Preposition upper marmon clamp.	5	
4.	Install ballute handling tool on ballute, attach RMS and remove ballute from its shipping container.	15	1 + 00
5.	Transfer ballute from stores to work area. Position ballute at rear of OTV.	10	
6.	Verify operation of ballute installation/jettison mechanism (4 ea @ 5)	20	
7.	Install ballute over heat shield structure. (Interface ballute with ballute installation/ jettison mechanism and drive forward. Remove ballute handling tool).	30	2 + 00
8.	Verify position of lower ballute interface.	5	
9.	Remotely tighten lower marmon clamp	5	
10.	Remove shipping restraint from upper ballute fabric and stow.	10	
11.	Unfold upper ballute fabric and position upper ballute on OTV.	20	
12.	Install upper marmon clamp over upper ballute bead and seat.	5	
13.	Torque upper and lower marmon clamps to specifications.	10	
14.	Connect ballute gas supply line and leak check	30	3 + 25
15.	Connect ballute separation devices (1 upper marmon clamp cutter, 1 corset line cutter, 1 gas line cutter) 3 units @ 10 per	30	

TABLE 2.2.4-3 BALLUTE INSTALLATION CONTINUED

	TASK	Minutes	Hrs + Min
16.	Verify ballute separation device interface 3 units @ 5 per	15	
17.	Stow tools.	30	4 + 40

Personnel Requirements:
2 EVA and 1 IVA

Tool Requirements:
1. Mobile Robots
2. Ballute Handling Tool
3. Astronaut Foot Restraint/Control Panel
4. Remote Manipulator System (RMS)
5. Miscellaneous hand tools

inspection and removal of the entire brake in order to gain access to the main engine and replacement of the flex TPS on the brake every fifth flight.

Visual Inspection. The key difference of either the lifting or shaped brake configuration relative to the ballute configuration is the relative surface areas.

The lifting brake and shaped brake configurations can be approximated by two spherical segments. (See figure 2.2.4-5, Assumed Brake Shape). The area to inspect becomes:

$$A = (2)(3.14)(r_1 h_1 + r_2 h_2).$$

r_1 = plan view radius of the brake = 20 ft (assumed)

h_1 = height of one spherical segment = 20 ft (assumed)

r_2 = radius of the brake = 28 ft (assumed)

h_2 = height of second spherical segment = 8 ft (assumed)

The area to be inspected equals:

$$(2)(3.14)(20 \text{ X } 20 + 8 \text{ X } 28) = 3920 \text{ ft}^2$$

The time to visually inspect equals:

$$3920\text{ft}^2 \div 6\text{ft}^2/\text{min} = 654 \text{ minutes}$$

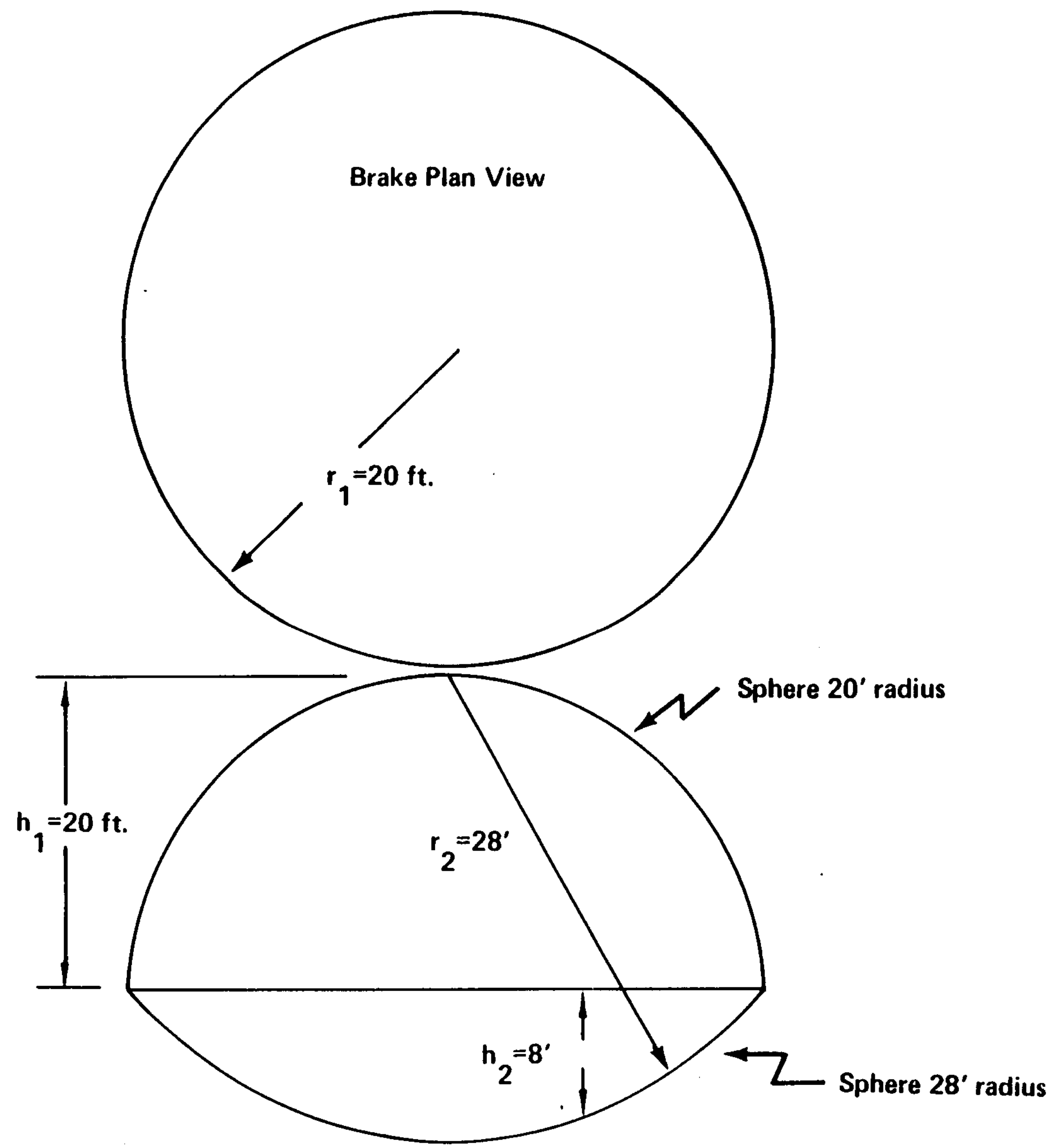
The time to position and stow the inspection camera is 15 and 6 minutes, respectively.

The total time required for inspection of the lifting or shaped brake configuration is:

$$\frac{15 + 654 + 6}{60} = 11.25 \text{ hrs.}$$

The inspection operation assumes one person IVA.

Remove and Replace Lifting Brake. Removal of the entire lifting brake is necessary in order to gain access to the main engine. Table 2.2.4-4 depicts the tasks and task durations necessary to remove and replace a lifting brake. The personnel and tool requirements are identical to those required to remove a heat shield from the Ballute configured OTV. Assumptions applicable to the timeline include:



Area = $2\pi rh$ = area of the curved surface of a spherical segment of height h and radius of sphere

Figure 2.2.4-5 Assumed Brake Shape Geometry

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TABLE 2.2.4-4 REMOVE AND REPLACE LIFTING BRAKE

(REQUIRED ACTION FOR ENGINE CHANGEOUT - LIFTING BRAKE CONFIGURATION)

	TASK	Minutes	Hrs + Min
1.	Remove tools and aeroshell handling tool from stores, prepare and checkout mobile robot(s), astronaut foot restraint/control panel, verify engine nozzles are retracted and engine door is open.	30	
2.	Disconnect electrical power connector from OTV to brake.	5	
3.	Attach aeroshell handling tool to lifting brake (3 attach points @ 5 min each)	15	
4.	Open Hangar door and position RMS. (Parallel activity)		
5.	Attach RMS to aeroshell handling tool.	5	
6.	Remove structural connectors (threaded studs) and stow. (4 connectors @ 5 min each)	20	
7.	Positon EVA personnel for brake removal	10	
8.	Remove brake from OTV with RMS.	10	1 + 35
	May require a mechanism (screw jacks) on the OTV to "drive" the brake structure off if the fit is too tight. In this case the OTV mechanism would "drive" until the brake is sufficiently loose to allow the RMS to continue the removal.		
9.	Move lifting brake to storage pedestal and position.	10	
10.	Secure lifting brake to storage pedestal. Remove RMS. (4 hold down bolts @ 5 min)	20	2 + 05

PROCEED WITH ENGINE CHANGEOUT

When Engine Changeout is complete, transfer the RMS to the lifting brake storage pedestal and:

11.	Connect RMS to aeroshell handling tool and remove hold down bolts. (4 @ 5 min each)	20	

TABLE 2.2.4-4 REMOVE AND REPLACE LIFTING BRAKE (CONTINUED)

	TASK	Minutes	Hrs + Min
12.	Transfer lifting brake to outside the OTV hangar.	10	
13.	Visually inspect lifting brake. Position the lifting brake and EVA personnel for lifting brake-to-OTV mate.	10	
14.	Move lifting brake structure forward to OTV tank set mating structure.	10	
15.	Position EVA personnel for installation of connectors.	15	1 + 05
16.	Install connectors. (4 bolts @ 10 min)	20	
17.	Tighten connectors and verify connector torques. (4 bolts @ 10 min)	40	2 + 05
18.	Remove RMS and aeroshell handling tool.	15	
19.	Connect electrical power connector from OTV to brake.	5	
20.	Apply electrical power to OTV. Verify door mechanism operation.	10	
21.	Extend engine nozzles, verify clearances, retract engine nozzles, shut down OTV electrical power.	15	
22.	Stow tools, remove RMS from hangar and close hangar door.	30	3 + 20

Personal requirements:
2 EVA and 1 IVA
Tool Requirements:
1. Aeroshell Handling Tool
2. Mobile Robot(s)
3. Astronaut Foot Restraint/Control Panel
4. Remote Manipulator System (RMS)
5. Miscellaneous hand tools

a. There is hard point interface inside the engine door(s) which can be accessed from the outside. This hard point mates with an aeroshell handling tool.
b. The RMS is used to position the lifting brake. EVA personnel serve as controllers and scanners. They cannot manhandle the lifting brake because of its construction.
c. The lifting brake is stored on a pedestal which interfaces with the brake structure at the same hard points where the brake structure interfaces with the OTV structure.
d. The lifting brake structure attaches to the OTV tankset at four points. It attaches with studs which need to be properly torqued. Shimming is not necessary.

2.2.4.3 Shaped Brake OTV

Visual inspection for the shaped brake OTV is judged to be the same as for the lifting brake. Engine removal and replacement is easier than for either of the other two configurations because the engines are not behind any brake or heat shield. However, the entire brake of this concept must be replaced every 20 flights (study groundrules). The associated time is the same as that specified in section 2.2.3.

2.2.4.4 Turnaround Comparison

Figure 2.2.4-6 compares the relative turnaround effort for each of the three SBOTV configurations. It reflects the installation of a new ballute after every flight versus the periodic replacement of the Thermal Protection System (TPS) on the other configurations.

The chart also reflects the current uncertainty and complexity involved in replacing the shaped brake modularized segments. A more detailed lifting brake design with a deeper analysis may impact the relationship between the lifting brake and shaped brake TPS periodic replacement. Replacement of a lifting brake TPS by ground fabricated segments versus space installed TPS fabric appears to be a more viable option.

The equivalent earth crewtime is included so as to provide a "sanity check" with which ground processing people can identify.

2.2.4.5 Integration Operations

The final integration operations include spacecraft (payload) mating and interface verification, loading of consumables and mission data. No significant difference exists between the SBOTV concepts.

CONFIGURATION	UNIQUE FEATURES	EVA CREWTIME (MANHOURS)	IVA CREWTIME (MANHOURS)	EQUIVALENT EARTH CREWTIME (MANYEARS) 2
BALLUTE	● INSTALL BALLUTE AND R&R ORU	26	23	17(EVERY FLIGHT)
	● R&R ENG, HEAT SHIELD, AND ORU	58	39	36(EVERY 20 FLIGHTS)
LIFTING BRAKE	● BASIC MAINTENANCE R&R ORU	12	21	10 (EVERY FLIGHT)
	● R&R BRAKE TPS AND ORU	172	116	105 (EVERY 5 FLIGHTS)
	● R&R BRAKE AND TPS, ENG., HEAT SHIELD, AND ORU	200	130	122 (EVERY 20 FLIGHTS)
SHAPED BRAKE	● BASIC MAINTENANCE R&R ORU	12	21	10 (EVERY FLIGHT)
	● R&R AEROSHELL, ENG. AND ORU	120	90	75(EVERY 20 FLIGHTS)

1 PROCESSING INCLUDES POST-FLIGHT/INSPECTION/REFURBISHMENT

2 COST BASIS: 1 EVA HR = 6 EARTH MAN MONTHS
1 IVA HR = 2 EARTH MAN MONTHS

Figure 2.2.4-6 Space Processing Comparison SBOTV

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2.2.5 SBOTV Tanker Ground Processing

A large portion of the propellant for a SBOTV is delivered to the Space Station storage system via a "tanker". The physical description of the tanker is presented in Section 3.0. The ground processing required by a SBOTV Tanker includes:

a. Initial Assembly and Checkout,
b. Interface Verification,
c. Payload Changeout Room Operations,
d. STS Launch Pad Operations,
e. Post-Landing Operations, and
f. Refurbishment Operations.

2.2.5.1 Tanker Ground Processing Groundrules/Assumptions/Derived Requirements

The analysis of the Tanker Ground Processing is based on the following:

a. Tanker ground operations shall not impact the STS timeline.
b. STAR 27 and VSTAR 10 Level III Assessment Timelines are used as a general baseline for STS related timelines.
c. Tanker Interface Verification is accomplished in the Vertical Processing Facility to utilize existing CITE. It is accomplished only on the initial flight of a Tanker.
d. Timelines are based on a "mature" operation with no allowance for "site activation/ procedure validation" activities.
e. The tanker is fueled with LO_2 and LH_2 on the launch pad parallel with STS propellant loading during "Shuttle Launch Countdown".
f. The tanker is assembled at an off site location and is shipped to the launch site in the following subassemblies:
    1. Tank assembly (which includes LH_2, LO_2, and Helium tanks, the required instrumentation and plumbing, plus an OMV interface),
    2. Hypergol Tank Assembly, and
    3. Airborne Support Equipment.
g. The ASE is the equipment necessary to interface the cryogenic fuel lines, dump system, and data links (instrumentation between the tanker and the Orbiter) and includes the required aft flight deck equipment.
h. The tanker processing facility is utilized for initial assembly and checkout, refurbishment of the tanker and the ASE, and storage of the units as necessary. It is a "clean" facility with work stands and access platforms.

i. The tanker has provisions for hypergol fuels. The initial fill and passivation of the hypergol tank assembly is performed prior to installation of the tanks. Subsequent filling operations are performed in the refurbishment facility.

2.2.5.2 Processing Timeline and Effort

The top level processing operations timeline is shown in Figure 2.2.5-1. The timeline indicates that turnaround of the SBOTV Tanker is approximately seven calendar weeks. it is highly dependent on STS and Tanker offload timelines (STS Launch Pad and MIssion Operations as well as Post Landing Operations). The main thrust of the performed analysis was directed toward the Refurbishment Operations. The timelines assume vertical integration with the Orbiter Bay at the Launch Pad. There is no real reason that the tanker could not be horizontally integrated with the Orbiter Bay in the Orbiter Processing Facility. In either scenario the integration and STS interface verification can be accomplished well within STAR 27 Level III Assessed cargo processing timelines.

The tanker ground processing plan has the following key elements:

a. One-time cryogenic tank load/drain operations.
b. Hypergol load off-line to STS operations and prior to pad operations.
c. Integral ASE and tank assembly structure, plumbing, and instrumentation.
d. One-time orbiter interface (CITE) verification.
e. Quick disconnect, zero entrapment cryogenic connections.

The tanker key elements for processing are similar to the GBOTV key elements. From a ground processing viewpoint, the SBOTV Tanker is basically a GBOTV minus the engines and avionics.

The processing effort in terms of calendar weeks per flight is shown in Table 2.2.5-1. The effort involving the STS is calculated using a two shift, 7 X 12 work schedule. The remaining effort is calculated using a single shift, 5 X 8 work schedule. Table 2.2.5-2 indicates the skill classification and numbers of processing personnel. The ground processing manpower requirements assume that the Tanker processing is accomplished in conjunction with some "larger" processing effort which provides the needed administrative, logistics, and management support. Ground processing of the OTV Tanker as a "Stand-alone" operation appears to be a very inefficient, high per flight cost operation.

The recurring ground processing of the tanker is determined to require 2.5 man years of effort per flight:

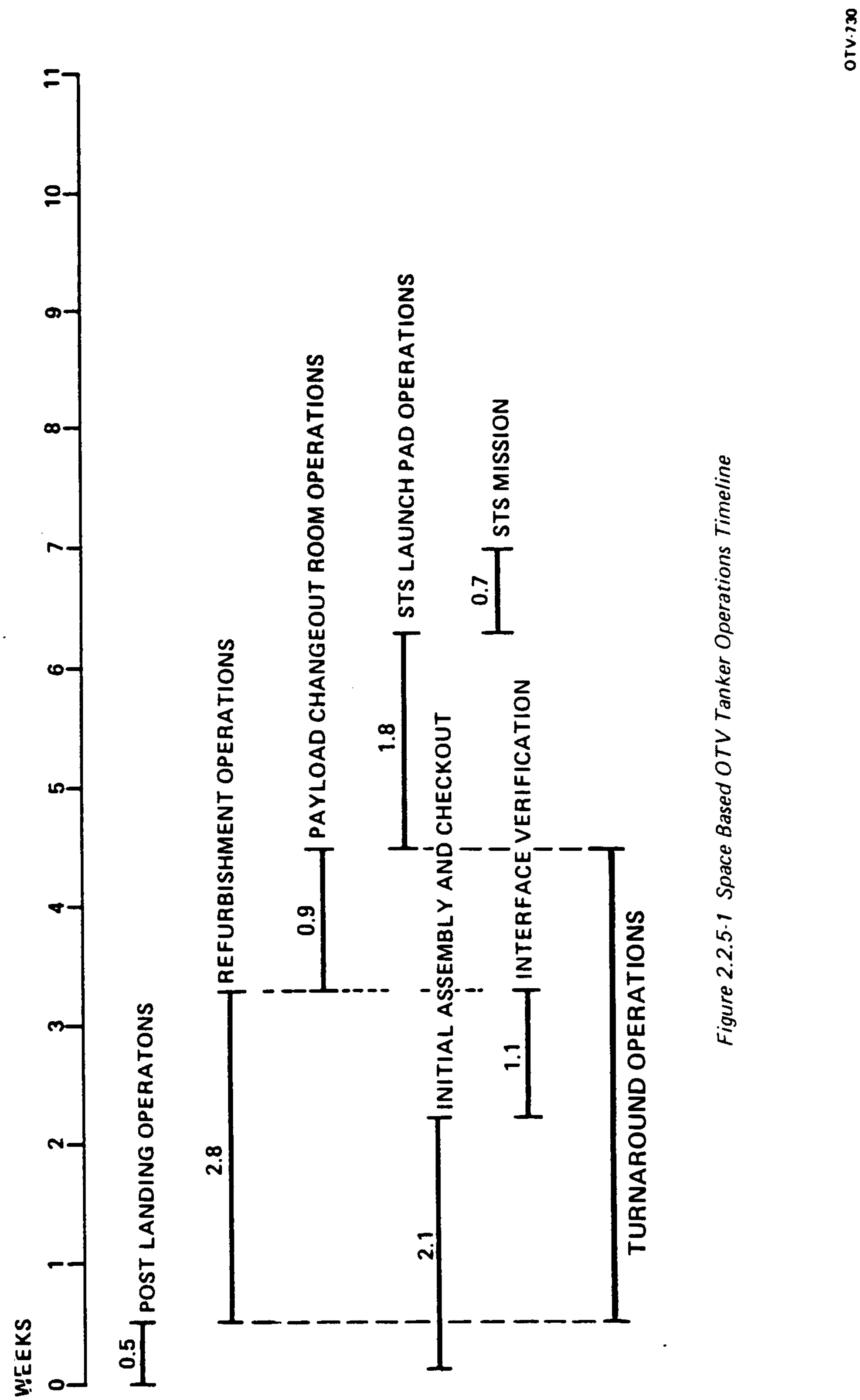

Figure 2.2.5-1 Space Based OTV Tanker Operations Timeline

Table 2.2.5-1. SBOTV Tanker Ground Processing Effort

MAJOR ACTIVITY	WORK SCHEDULE	NUMBER OF SHIFTS	TIMELINE HOURS	CALENDAR WEEKS PER FLIGHT
INITIAL ASSEMBLY AND CHECKOUT	5X8	1	84	2.1
INTERFACE VERIFICATION	5X8	1	44	1.1
POST LANDING OPERATIONS	7X12	2	72	0.43**
STS LAUNCH PAD OPERATIONS	7X12	2	296	1.8*
← TURNAROUND →				
REFURBISHMENT OPERATIONS	5X8	1	112	2.8
PAYLOAD CHANGEOUT ROOM OPERATIONS	5X8	1	36	0.9
TURNAROUND		TOTALS	148	3.7

*Equivalent 5X8 time equals 4.77 calendar weeks
**Equivalent 5X8 time equals 1.44 calendar weeks

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Table 2.2.5-2. SBOTV Tanker Ground Processing Manpower Requirements

SKILL CLASSIFICATION	HEADCOUNT
ENGINEER	2
PLANNER/SCHEDULER	1
QUALITY/INSPECTOR	2
TECHNICIANS	8
TOTAL	13

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$$\frac{13 \text{ X } (1.14 + 2.8 + 0.9 + 4.77)}{50} = 2.5 \text{ manyears/flight}$$

The effort is expended over approximately 5 weeks of calendar time per flight. The Turnaround timeline (Refurbishment and Payload Changeout Room Operations) is 148 hours.

2.2.6 Facility Requirements

Facility requirements and accommodations for the SBOTV are defined in Volume IV of this reports.

2.2.7 KSC OTV Operations Study Impact

OTV processing/turnaround operations was also addressed in a NASA KSC/Boeing study (ref 6). This effort was completed approximately 6 months after the system level OTV study effort concerning these operations. The results of the KSC study and their impact are summarized below.

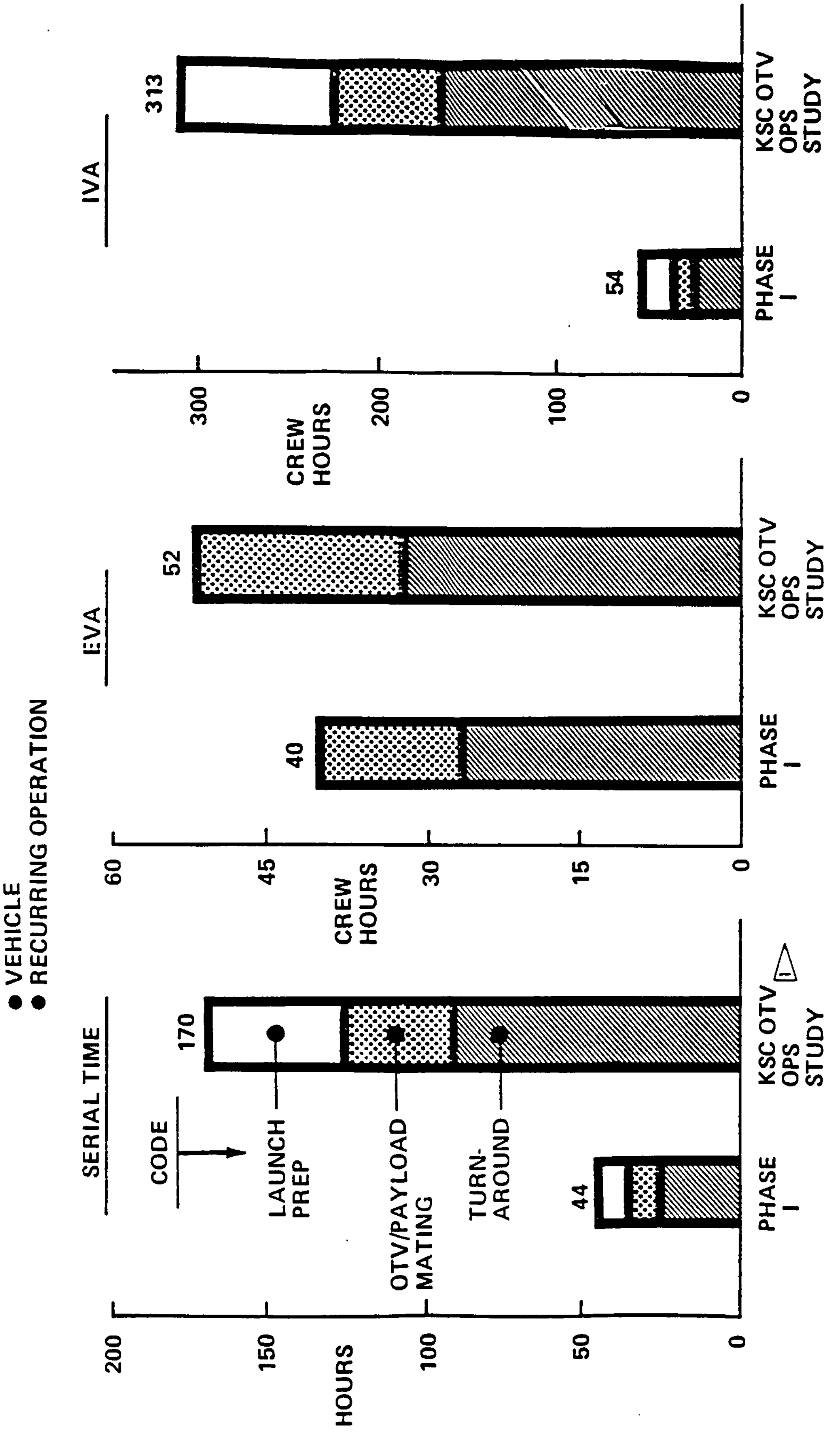
The KSC OTV Operations study focused on a SB OTV using a symmetrical lifting brake rather than a ballute device for aeroassist. The remainder of the vehicle in terms of main propulsion, avionics, electrical power and RCS were very similar to the Boeing SB OTV concept.

The on-orbit processing time for the SB OTV as found in the two studies is shown in Figure 2.2.7-1. In summary, the KSC Operation study resulted in more hours than the OTV Concept Definition Study and is generally attributed to a more in-depth analysis, since that was the whole purpose of that study. The serial time was nearly four times the duration found in the OTV study.

From a cost standpoint, the important factors are the amount of time associated with EVA and IVA. The EVA crew hours (includes 2 people) were 35% higher in the KSC study while the IVA (1 person) was nearly 6 times the effort. About the same time as the KSC study was finishing, the Space Station program also revised the cost per EVA person hour to $75K and an IVA hour to $17K. The result was that a typical recurring turnaround cost for the SB OTV was over $9 million.

2.3 LAUNCH PROCESSING OPERATIONS SUMMARY

The study objective was to uncover discriminators resulting from OTV configurations and resultant processing requirements. Analyses performed were relative comparisons versus absolute determinations. As the vehicle design/configuration



1 FROM BAC–KSC "ORBITAL TRANSFER VEHICLE LAUNCH OPERATIONS STUDY", DATED MARCH 7, 1986, CONTRACT NO. NAS10–11165

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Figure 2.2.7-1 SB OTV On-Orbit Processing matures, additional analyses should refine the relative comparisons and develop realistic absolute cost values. As with any operational analysis, the analysis is iterative with operational requirements impacting vehicle design and the OTV design reimpacting the operations.

The cost of Space Station servicing will "motivate" any program requiring Space Station processing (SBOTV or GBOTV with auxiliary tank) to:

a. Develop streamlined autonomous vehicle self-check equipment and procedures (hardware and software),

b. Design simplified structural, mechanical, and electrical interfaces, and

c. Develop robotic concepts for repetitive processing tasks.

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3.0 PROPELLANT LOGISTICS

Propellants for the space based OTV will be stored at the space station. Maintaining cryogenic propellants at the Space Station and transferring these propellants to the OTV are major factors in the OTV operations costs. The propellant logistics studies addressed the key issues and problems associated with delivery of cryogenic propellants to storage tanks at the Space Station, transfer of propellants to the storage tanks, boiloff during storage and transfer of propellants to the OTV.

3.1 PROPELLANT HANDLING AND INVENTORY REQUIREMENTS

An example of the propellant handling schedule at the Space Station for the year (2001) is shown in Figure 3.1-1. During this year there were 9 OTV loadings, 7 Shuttle tanker deliveries, and 13 deliveries of scavenged propellants. OTV missions during this year included: 3 multiple manifest missions with 10,000 lbm payload; 5 GEO delivery missions with 20,000 lbm payload and 1 mission with 7,000 lbm delivered; and 4,500 lbm returned from GEO. Propellant losses which are associated with each of the deliveries, OTV loadings, and annual boiloff are the logistics factors which contribute to the total cost of supplying OTV propellants.

An inventory of propellants is required at the Space Station to support OTV operations with schedules not coupled to Shuttle tanker deliveries, in so far as possible. The propellant inventory required was developed with the assumption that sufficient propellant should be maintained available to support two planned OTV missions if a Shuttle tanker flight could not be flown. The two missions considered included a low "g" mission and a multiple manifest mission. These missions required a total propellant quantity of over 121K-lbm for the OTV flights. Delivery of propellant via scavenging flights between OTV flights as well as allocation of unusable propellant (residuals) lead to a total propellant inventory requirement of 160,760 lbm, as shown by table 3.1-1.

The inventory requirement to support a manned mission was based on an assumed requirement to provide a backup rescue capability. The total OTV loading requirement for the manned mission with rescue is 129,300 lbm. The critical timing of the rescue mission does not permit any propellant resupply. The inventory requirement to start the manned mission is 135,180 lbm including allowance for system cooldown and residuals. The possibility of a mission slide was considered and an additional capacity of 50,000 lbm included to take advantage of two maximum scavenging opportunities. The total inventory requirement of 185,180 lbm shown by Table 3.1-1 was taken as the propellant depot sizing requirement.

7 TANKER DELIVERIES	TOTAL	420,000 LBM
13 SCAVENGE DELIVERIES	TOTAL	178,100
DELIVERED	TOTAL	598,100
9 OTV LOADINGS (YEAR 2001)		534,355
ANNUAL BOILOFF		14,600
INVENTORY INCREASE		49,145 LBM

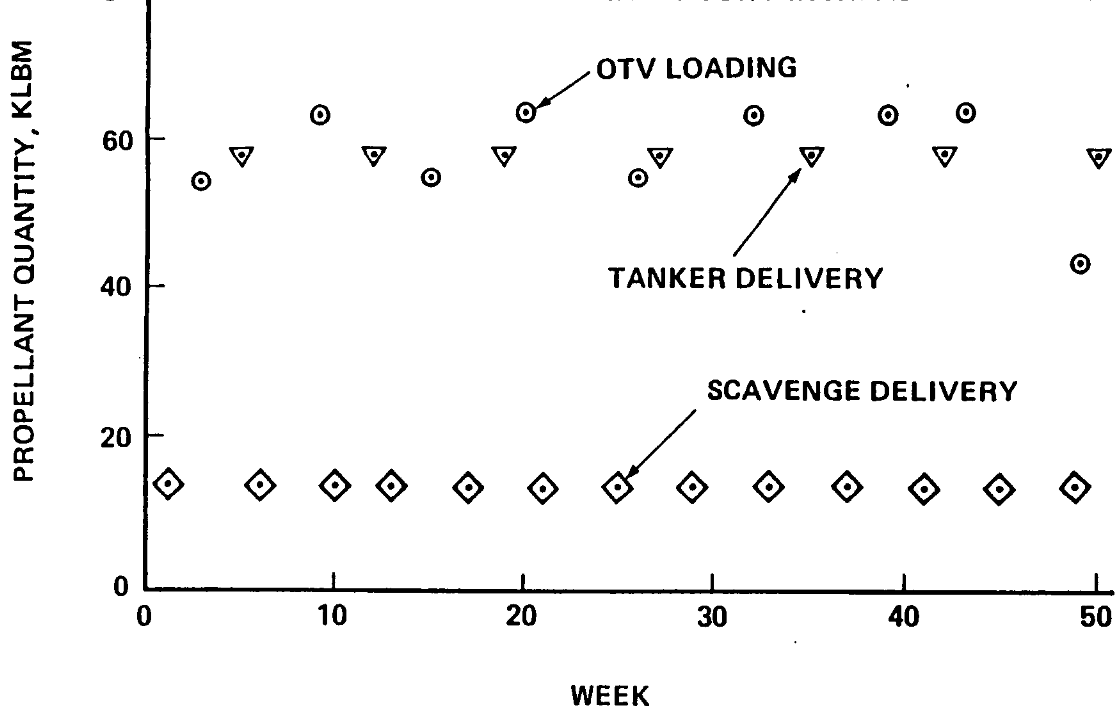

Figure 3.1-1 Typical Propellant Handling Schedule

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Table 3.1-1 Orbital Storage Propellant Inventory Requirement

MISSION REQUIREMENT / SYSTEM REQUIREMENT	MANNED MISSION AND RESCUE WITHOUT RESUPPLY	LOW "G" MISSION AND MULTIPLE MANIFEST MISSION WITH NOMINAL SCAVENGE RESUPPLY
PROPELLANT LOADING FOR TWO MISSIONS	129300	118880
CHILLDOWN OTV AND SYSTEM FOR TWO MISSIONS	2280	2280
STORAGE TANKS RESIDUALS	3600	3600
RESUPPLY ALLOWED	0	14000
MINIMUM INVENTORY AT FIRST MISSION START	135180	110760
ADDITIONAL SCAVENGE SUPPLY ALLOWED	50000	50000
TOTAL CAPACITY	185180	160760

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3.2 DELIVERY AND STORAGE TRADES

3.2.1 Delivery Options

Two propellant delivery options were considered and are characterized in figure 3.2-1. The first method is to take the Orbiter directly to the Space Station. In the OTV era, the Shuttle was assumed to have a lift capacity to 270nmi of 58,500 lbm. The tanker was assumed to have a mass fraction (propellant to total weight) of 0.86. Thus the net propellant delivered to the Space Station is 50,300 lbm.

The second method is to use the Orbital Maneuvering Vehicle to transfer the propellant tanker from the Orbiter to Space Station. The Shuttle, under the same assumptions made for the first method, would have a lift capacity of 72,000 lbm to 140nmi. Since the OMV would use 4,800 lbm of propellant to perform it's mission, and the overhead to deliver that 4,800 lbm is assumed to be 1,200 lbm, a total of 6,000 lbm must be subtracted from the Orbiter lift capability to arrive at the net useful payload capacity. Using the same mass fraction as the first method, the net propellant delivered is 56,700 lbm.

The first, or "Direct Insertion" method has a cost of one shuttle flight, or $68.5 million (midterm cost groundrules). The second, or "OMV Transfer" method, requires the use of the OMV at a cost of $1.5 million, in addition to the cost of a Shuttle flight. The cost per pound of propellant delivered is $1,362 for direct insertion vs. $1,235 for OMV transfer as shown in table 3.2-1 resulting in selection of the OMV transfer method for the remainder of the trade studies.

3.2.2 Resupply and Storage Options

Resupply Concepts. Two basic methods of propellant resupply are tank (1) exchange at the Space Station and (2) fluid transfer with propellants transferred from a tanker to permanent space based storage tanks. Two types of tanks are applicable to each method as shown by table 3.2-2.

Tankers used for propellant replenishment were all sized for 72,000 lbm Orbiter lift capability. The net propellant delivered depends on the tank type and whether the tank exchange or fluid transfer option is used. Major weight items of the alternative tanker concepts and the net propellant delivery capabilities are shown by figures 3.2-2 and Table 3.2-3. The delivered quantities include the effects of residuals and transfer losses including boiloff during the launch phase. Dewars deliver about 4,000 lbm less than MLI tankers due to the weight of the outer shell which must withstand sea level external

KEY ASSUMPTIONS

- STATION AT 270 NMI
- TANKER APPROX. 66,000 LBS

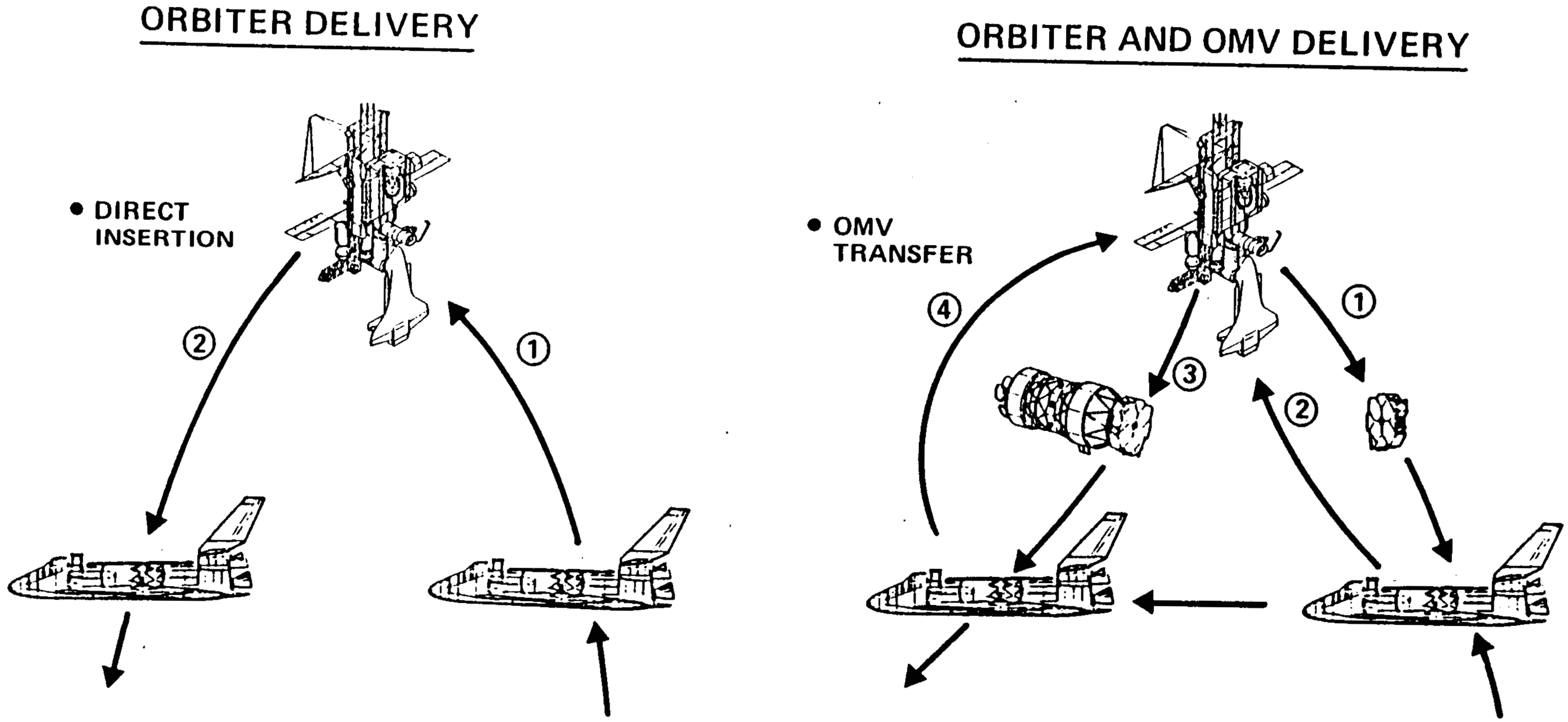

Figure 3.2-1 Propellant Delivery Options

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Table 3.2-1 Delivery Comparison

DIRECT INSERTION

- ORBITER LIFT CAPABILITY TO 270 NM: 58,500 LB
- λ' OF TANKER = 0.86
- NET PROPELLANT DELIVERED 50,300 LB
- COST OF FLIGHT $68.5 M
- COST PER LB OF OTV PROPELLANT: $1362

OMV TRANSFER

- ORBITER LIFT CAPABILITY TO 140 NM: 72,000 LB
- OMV PROPELLANT FOR TRANSFER 4800 LB
- λ' OF OMV RESUPPLY 0.80
- OMV PAYLOAD ELEMENT WEIGHT 6000 LB
- NET LIFT CAPACITY 66,000 LB
- λ' OF TANKER 0.86
- NET PROPELLANT DELIVERED 56,700 LB
- COST OF FLIGHT $68.5 M
- COST OF OMV USE $ 1.5 M
- COST PER LB OF OTV PROPELLANT: $1235

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Table 3.2-2 Resupply Options and Trades Propellant Delivery - Transfer - Storage

RESUPPLY METHOD	TANKER	STORAGE
TANK EXCHANGE	DEWAR	-----
TANK EXCHANGE	PURGED MLI	-------
FLUID TRANSFER	DEWAR	DEWAR
FLUID TRANSFER	PURGED MLI	PURGED MLI
FLUID TRANSFER	PURGED MLI	DEWAR

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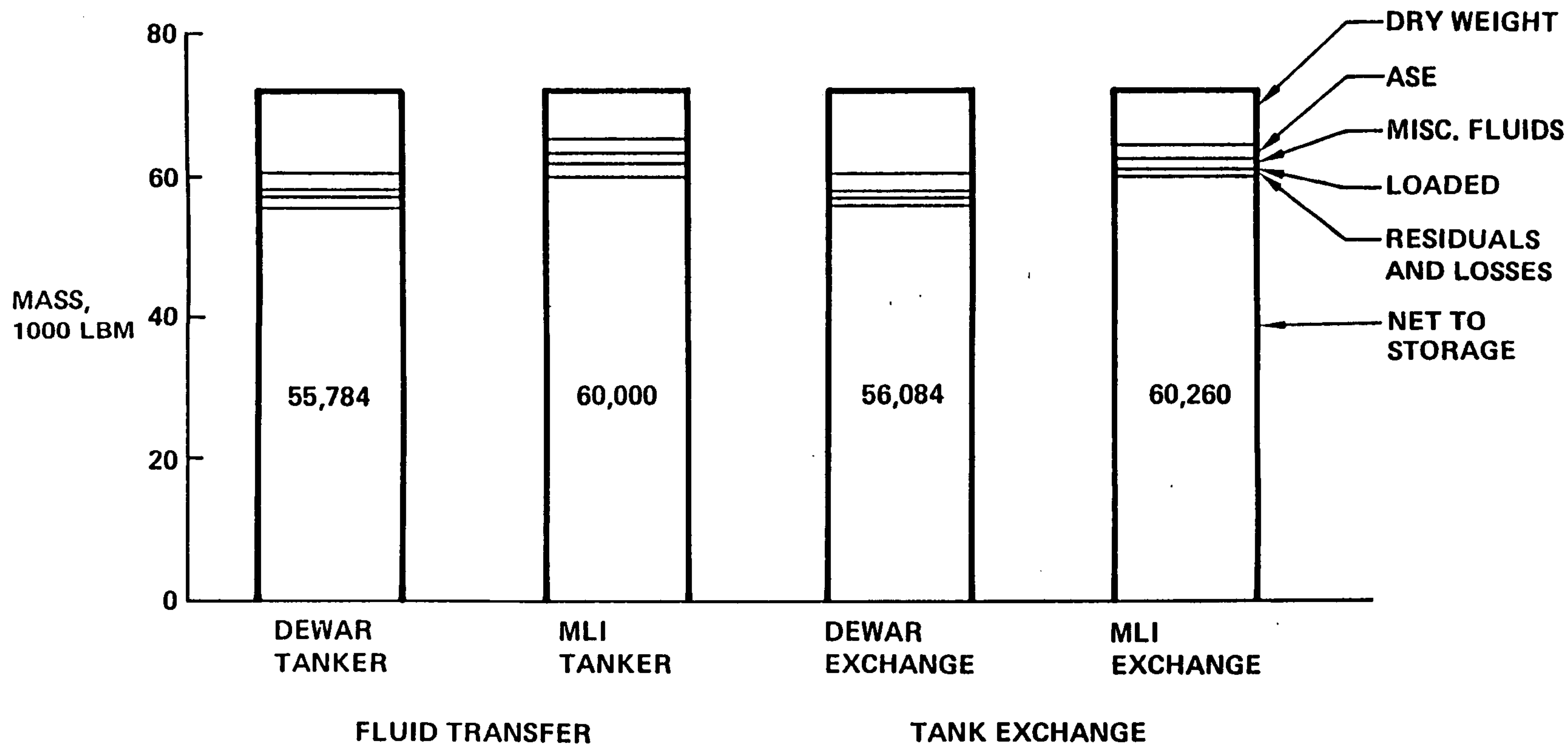

Figure 3.2-2 Propellant Replenishment Fluid Transfer Vs. Tank Exchange

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Table 3.2-3 *Propellant Delivery Options and Characteristics*

	TANK EXCHANGE TANKERS		FLUID TRANSFER TANKERS	
	DEWAR	PURGED MLI	DEWAR	PURGED MLI
STRUCTURE	,443 LBM	3,376 LBM	5,443 LBM	3,080 LBM
THERMAL CONTROL	2,254	420	2,254	420
AVIONICS	150	150	150	150
ELECTRICAL POWER	55	55	55	55
MPS TRANSFER SYSTEM	1,929	1,929	1,929	1,929
RCS TRANSFER SYSTEM	303	303	303	303
EPS TRANSFER SYSTEM	0	0	0	0
WEIGHT GROWTH MARGIN (15%)	1,520	934	1,520	891
TANKER DRY WEIGHT	11,655 LBM	7,168 LBM	11,655 LBM	6,828 LBM
ASE	1,900	1,900	1,900	1,900
MISC. FLUID (N_2H_4, N_2, He)	1,267	1,267	1,267	1,267
MPS PROPELLANTS	57,178	61,655	57,178	62,005
MPS RESIDUALS	1,080	1,180	1,080	1,180
MPS TRANSFER LOSSES (BOILOFF-CHILLDOWN-FLASHED)	14	525	314	825
NET MPS PROPELLANT TO STORAGE	56,084 LBM	60,260 LBM	55,784 LBM	60,000 LBM

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pressures on the vacuum annulus. The purged MLI tank exchange tanker includes a debris shield and is therefore heavier than the MLI tanker used for fluid transfer. Detailed discussions of the tanker structure and weight are contained in Volume II, Book 3.

Propellant Storage Concepts. Three tank concepts were investigated for propellant storage at the Space Station. Table 3.2-4 summarizes major features of the three concepts. Concept 1 has two hydrogen and two oxygen tanks forming two tank sets with 93,000 lbm hydrogen and oxygen capacity for each set at a mixture ratio of 6/1. These dewar type tanks are planned for dry launch so that the structure and thermal design is not compromised for the launch environment. The dry launch approach does not require internal tank baffles which would impact the liquid acquisition system. The large tank sizes are optimum for orbital storage and require a simpler fluid transfer plumbing system than other concepts requiring more than two tank sets. Two tank sets are needed for redundancy reasons to provide back up operational capability in the event of a tank failure.

Concept 2 uses dewar tanks which are launched loaded and are sized to the Orbiter lift capability. This configuration is applicable to either the tank exchange or the fluid transfer propellant resupply approach. Concept 2 requires three tank sets to satisfy the manned mission inventory requirement and has reduced ability to accommodate additional scavenging opportunities in the event of an OTV mission slide.

Concept 3 uses MLI only insulated tanks and assumes the tank exchange resupply method is used. This concept also required three tank sets at the Space Station to satisfy manned mission inventory requirements. The total capacity is nearly the same as Concept 1 and can accommodate nearly the same quantity of scavenged propellants.

The total annual orbital boiloff rate of the three concepts (shown by table 3.2-4) is a major factor affecting the total number of Orbiter tanker flights required. Concept 3 MLI insulated tanks orbital boiloff losses are much higher than the dewar Concepts 1 and 2 which differ by a small amount due to the tank sizes.

Comparison. Table 3.2-5 compares the propellant replenishment methods and the storage concepts on the basis of the number of Orbiter tanker flights required for the OTV program low mission model. The data include the effects of all propellant losses as well as the OTV loading requirements determined for each mission in the mission model. Concept 1 using an MLI tanker for resupply of two tank sets of large dewars at the Space Station requires the least number of propellant deliveries. The dewar tank

Table 3.2-4 Propellants Storage Concept Loss Comparisons

	CONCEPT 1 PERMANENT DEWAR STORAGE TANK	CONCEPT 2 DEWAR TANK EXCHANGE	CONCEPT 3 MLI PURGED TANK EXCHANGE
LAUNCH CONDITION	DRY	WET	WET
BOILOFF RATE LBM PER DAY PER TANK SET	20	14	130
NUMBER OF O_2/H_2 TANK SETS AT STATION	2	3	3
O_2/H_2 CAPACITY PER TANK SET	93,000	57,178	61,665
TOTAL O_2/H_2 CAPACITY AT STATION	186,000	171,534	184,995
NET O_2/H_2 DELIVERY PER STS TANKER	60,000	56,084	60,260
TOTAL ORBITAL BOILOFF RATE LBM/YEAR	14,600	15,330	142,350

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Table 3.2-5 STS Propellant Deliveries

CUMULATIVE DELIVERIES TO END OF YEAR *

YEAR	FLUID TRANSFER AT STATION: MLI TANKER TO DEWAR (1)	FLUID TRANSFER AT STATION: DEWAR TANKER TO DEWAR (2a)	EXCHANGE TANKS AT STATION: DEWAR TANKS (2b)	EXCHANGE TANKS AT STATION: MLI TANKS (3)
1997	5	5	5	6
1998	9	10	10	12
1999	13	14	14	18
2000	18	19	19	25
2001	25	26	26	34
2002	29	31	31	41
2003	36	39	39	49
2004	43	46	46	59
2005	49	53	52	67
2006	57	60	59	77
2007	63	68	67	85
2008	73	78	80	98
2009	82	88	87	110
2010	92	99	98	121

* INCLUDES OTV PROPELLANT, DELIVERY SYSTEM BOIL OFF AND TRANSFER LOSSES, STORAGE LOSSES AND OTV CHILLDOWN AND FILL LOSSES

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exchange method (Concept 2b) is next lowest with the MLI tank exchange approach (Concept 3) requiring the maximum number of deliveries. Concept 3 was judged not competitive with the other options due to the requirement for 29 deliveries more than Concept 1. The dewar tank exchange method (Concept 2b) required only 7 additional deliveries therefore more detailed costing analysis was required to determine which system was best.

Figure 3.2-3 and 3.2-4 are life cycle cost comparisons of the concepts 1 and 2b. Concept 1 which was selected as the baseline because of slightly lower total program cost but the alternative Concept 2b is very competitive and is considered to be a viable alternative. The program costs do not include the fluid transfer system at the space station. The baseline Concept 1 requires only two tank sets instead of three sets for Concept 2b therefore the baseline system would have some small cost advantage not shown by the cost data.

Other Concepts. Refrigeration was not considered during this study. Results of the FOTV study did show some cost benefit from refrigeration as indicated in figure 3.2-5. The conclusion of the FOTV study was, however, that refrigeration systems were high risk systems with uncertainties in performance which precluded recommendation of this approach. Refrigeration systems are not yet sufficiently developed to justify their recommendation. An alternative approach of capturing and compressing the boiloff losses was selected for the OTV propellant storage system. An analysis of the relative cost benefits of a reliquefaction system is shown in section 3.5.

3.3 Selected Systems Description

3.3.1 Propellant Transfer System

The propellant transfer system schematic shown by figure 3.3-1 is the configuration selected for propellant transfers to be accomplished at the Space Station. The system is arranged so that the tanker and OTV use a common docking port and the same interfaces for the required fluid transfers. Gases vented from the tanks due to boiloff and during fluid transfer operations are captured, compressed and stored at approximately 2000 psia. The compressed gases are used to effect pressurized fluid transfer from the tanker to the storage tanks or from the storage tanks to the OTV by selectively opening and closing appropriate valves. The system is intended to capture all gases vented from the tanks and therefore will not violate the Space Station no vent requirement. Implications of the no vent rule are further discussed in Section 3.4.

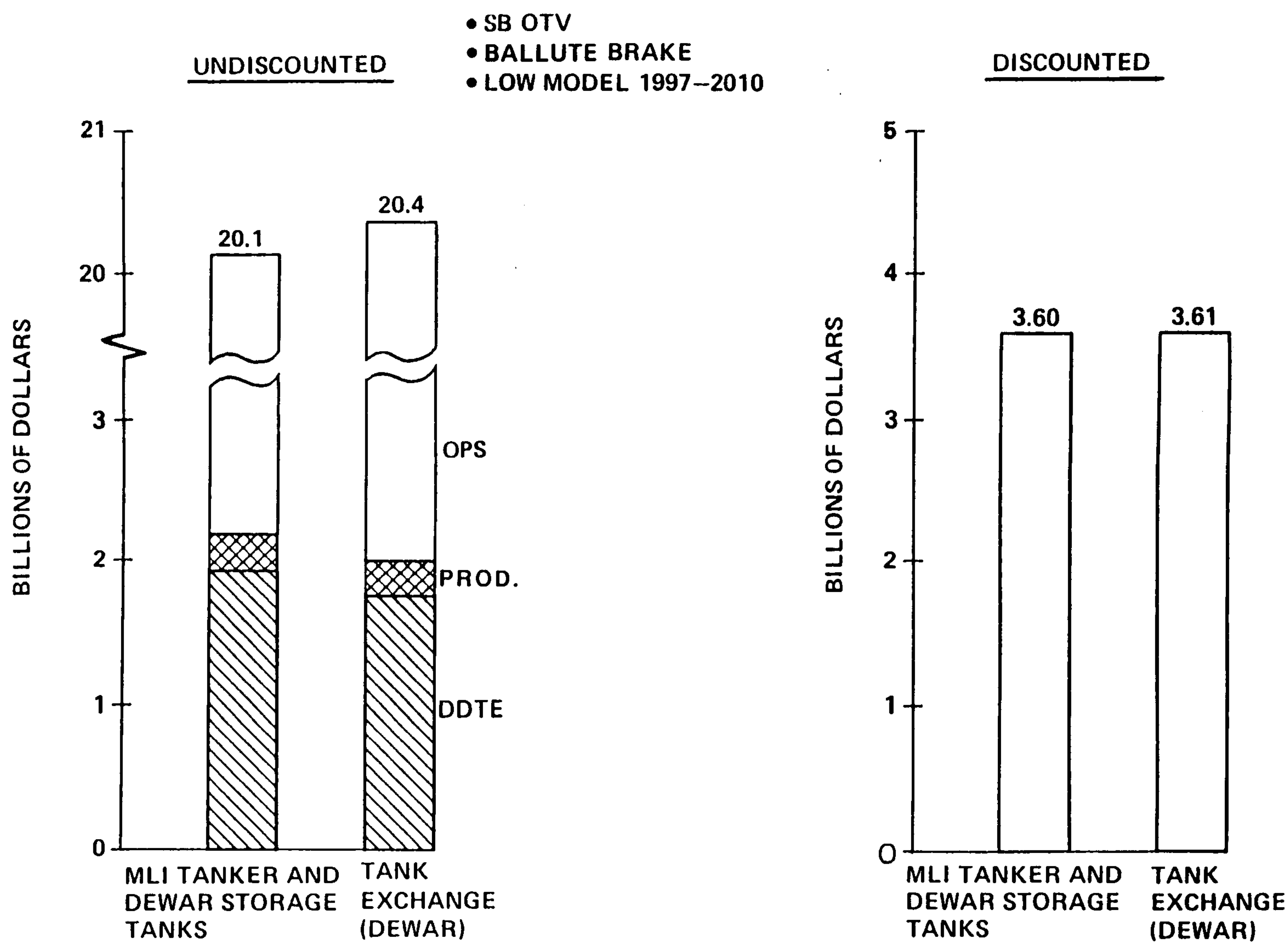

Figure 3.2-3 OTV Program LCC Comparison Propellant Delivery and Storage Influence

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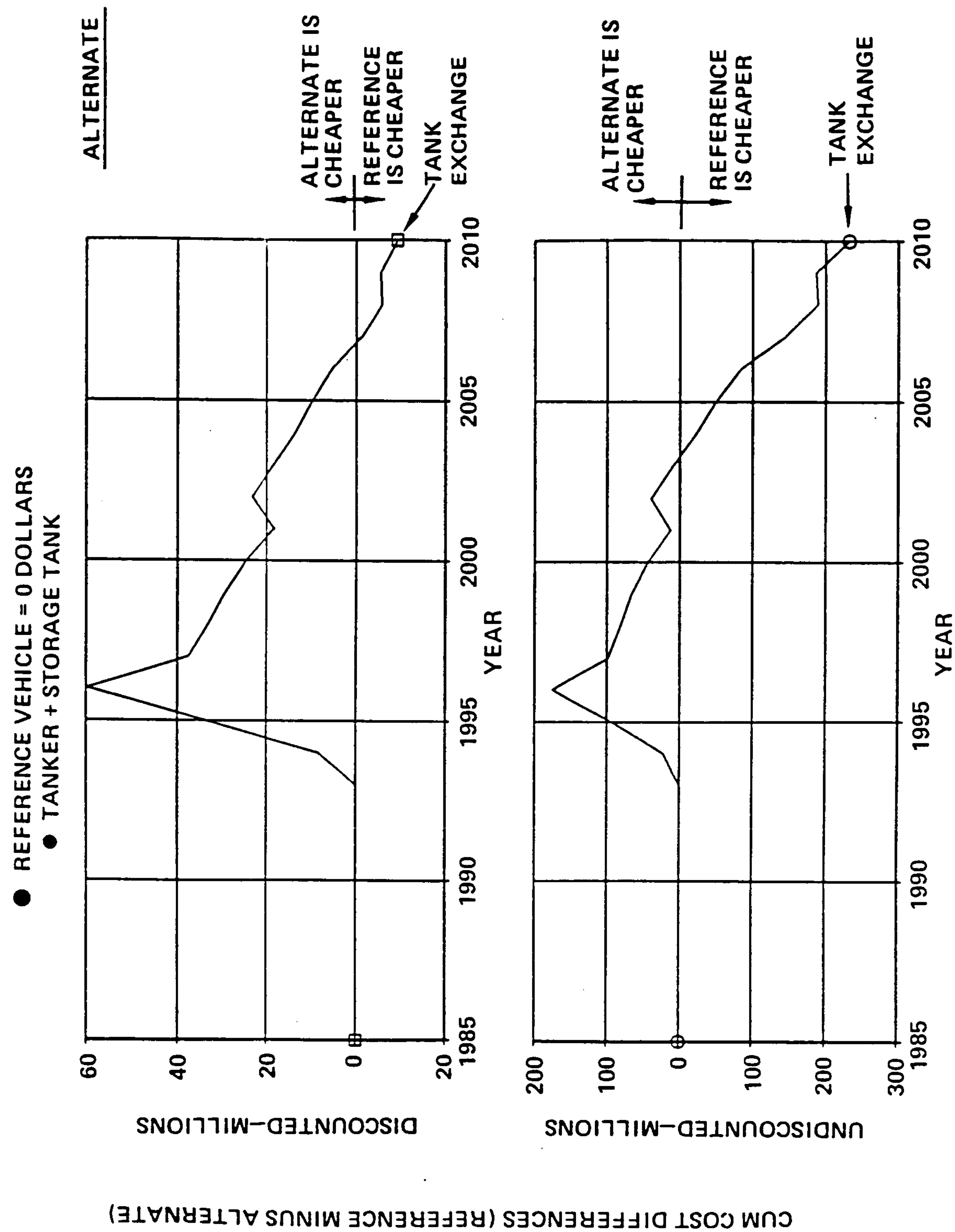
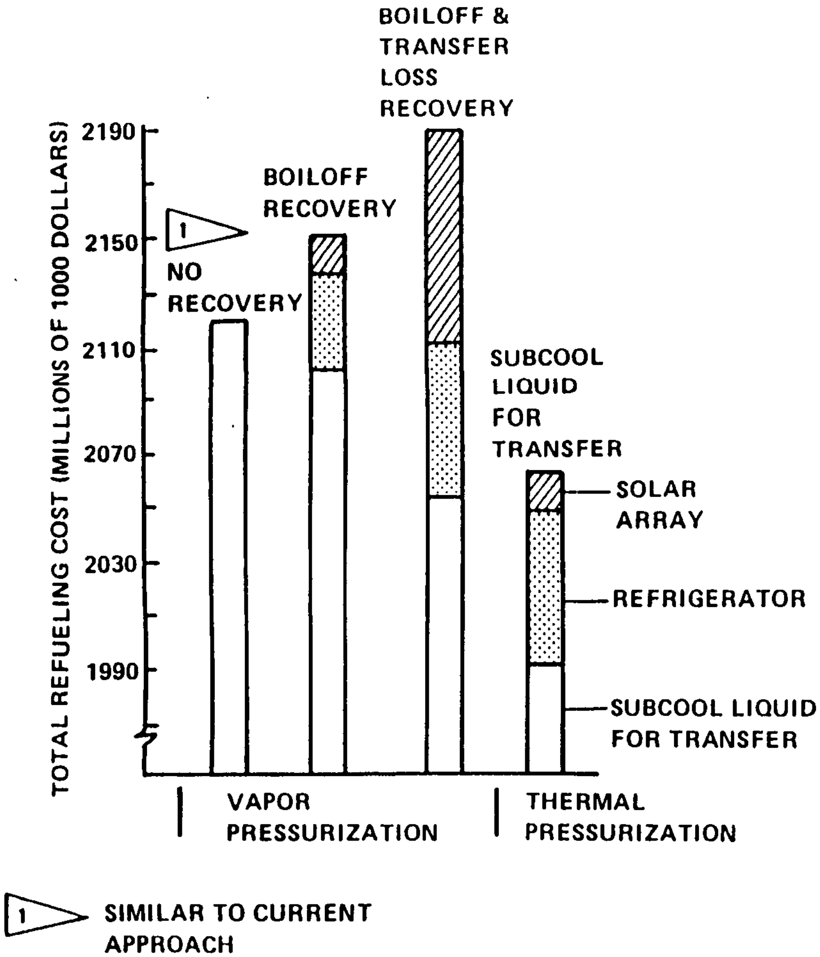


Figure 3.2-4 Time Phased LCC Comparison Propellant Delivery/Storage Trade

FOTV RESULTS



- RELIQUIFACTION OF VENTED PROPELLANT VAPORS INCREASED TOTAL PROPELLANT COSTS
- SUBCOOLING THE LIQUID TO REDUCE TRANSFER LOSSES AND BOILOFF RESULTED IN LOWER TOTAL COSTS
- REFRIGERATION SYSTEMS WERE NOT CONSIDERED IN THIS PHASE A OTV STUDY DUE TO HIGH RISKS AND UNCERTAINTY IN PERFORMANCE

Figure 3.2-5 Refrigeration Assessment for Propellant Loss Recovery

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OTV-711

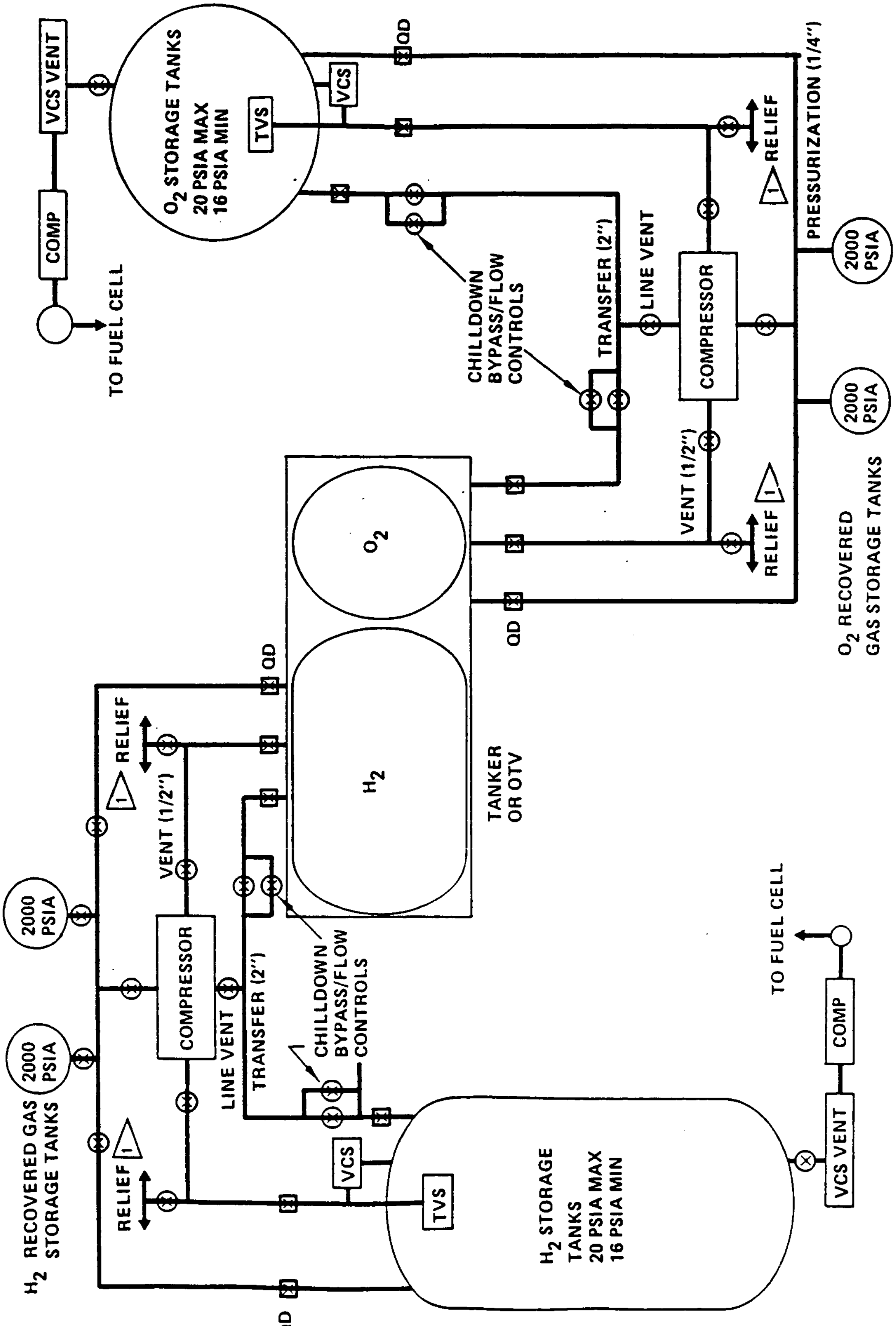


Figure 3.3-1 Propellant Transfer System Schematic

1 FOR EMERGENCY CONDITIONS

VCS = VAPOR COOL SHIELDS

3.3.2 Propellant Storage Tanks

The configurations of the Space Station hydrogen and oxygen storage tanks are shown by figures 3.3-2 and 3.3-3. Two tank sets will be permanently attached to the Space Station. The tanks will be launched empty and pressurized. Liquid acquisition devices consisting of eight screen channels are included in each tank to provide liquid at the outlets for fluid transfer in the low "g" Space Station environment. The dewar insulation annulus will be pressurized with helium during ground and launch operations to maintain insulation cleanliness and integrity. The insulation annulus will be vented to vacuum on orbit to obtain dewar conditions and thermal performance. Boiloff rates for these tanks were estimated based on operating vapor cooled shields. A hydrogen boiloff rate of 7 lbm per tank/day and an oxygen boiloff of 13 lbm per tank/day was estimated. Acceptance testing of the tanks thermal performance will be accomplished on the ground in a vacuum chamber with the insulation evacuated and repressurized after test completion.

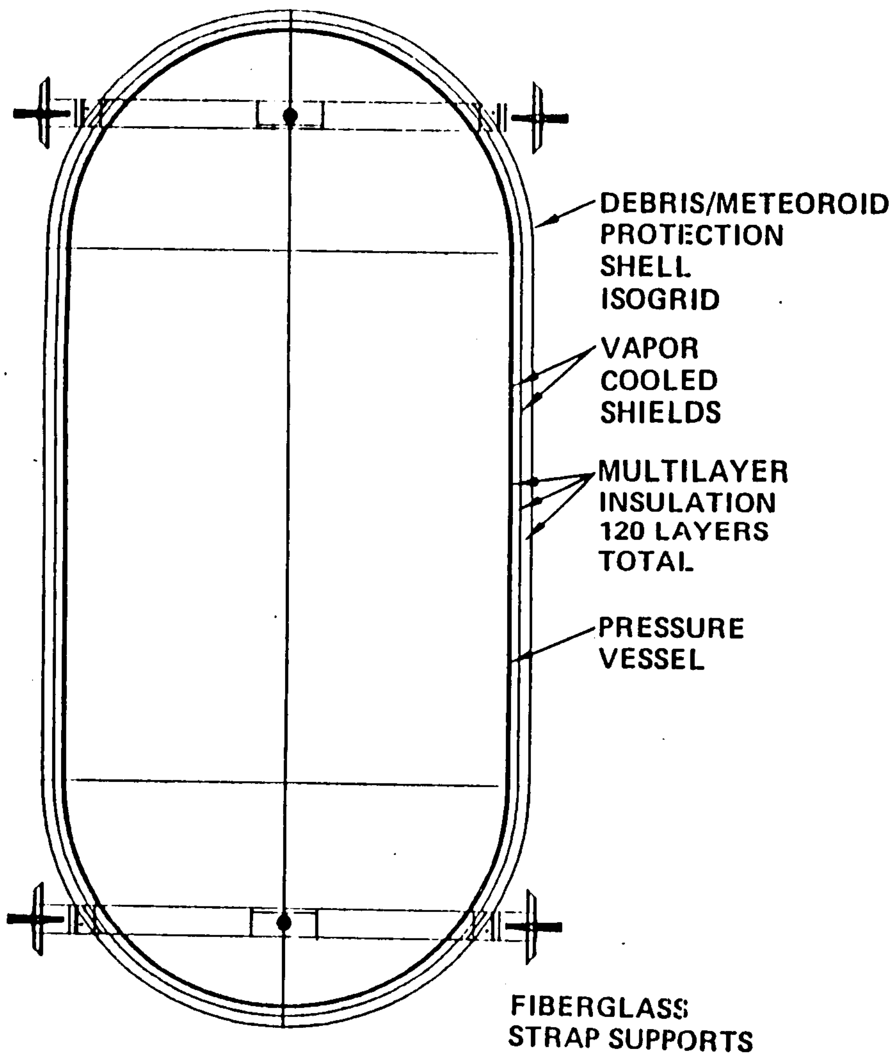
3.3.3 Propellant Tanker

The baseline MLI insulated tanker concept is shown by figure 3.3-4. Detailed descriptions of the tanker structure and weight are included in Volume II, Book 3, Sections 3.2.1 and 2.2.7. Each tank includes a liquid acquisition device with eight screen channels for fluid transfer at the Space Station. The tank insulation system was selected assuming 30 layers of MLI per inch which resulted in 210 lbm boiloff during the launch phase. Achieving this low MLI density may be compromised by system supports and plumbing therefore boiloff was estimated for an MLI density of 60 layers/inch. Boiloff with the higher density insulation was estimated at 395 lbm during the launch phase and this value was used for propellant loss accounting.

A schematic of the tanker plumbing system is shown by figure 3.3-5. The system includes 53 cubic feet of helium storage at 4000 psia to provide abort dump capability for both propellants if required for a return to launch site launch abort. The system shown includes interfaces required for ground loading and propellant transfers at the Space Station.

3.3.4 Propellant Handling Factor

The efficiency of the propellant logistics operations is defined as the propellant handling factor which deals with the ratio of total propellant required including losses to the amount of OTV main impulse propellant. Contributors to this factor are presented



DESIGN PARAMETERS

- PRESSURE VESSEL
  - DIAMETER, 13 FT
  - LENGTH, 28.93 FT
  - WE GHT, 1397 LBM
- DEBRIS/METEOROID SHELL
  - DIAMETER 14.33 FT
  - LENGTH 30.26 FT
  - WEIGHT, 1652 LBM
- CAPACITY AT 17.5 PSIA
  - 13286 LBM WITH 7% ULLAGE
- INSULATION SYSTEM
  - 120 LAYERS MLI
  - 2 VAPOR COOLED SHIELDS WITHIN MLI
  - BOILOFF ~ 7 LBM/DAY
  - WEIGHT, 1114 LBM
- LIQUID ACQUISITION SYSTEM
  - 8 CHANNELS ON MERIDIANS
  - CHANNELS 8 IN. BY 2 IN.
  - 2 SCREENS 325 x 2300 ONE SIDE OF CHANNEL
  - WEIGHT, 781 LBM
- TOTAL TANK WEIGHT, 5686
- ASE WEIGHT 598 LBM
- DEVELOPMENT COST, \$106.3 x 10^6
- PRODUCTION COST, \$9.9 x 10^6 FIRST UNIT

Figure 3.3-2 Space Station Hydrogen Storage Tank Baseline Concept

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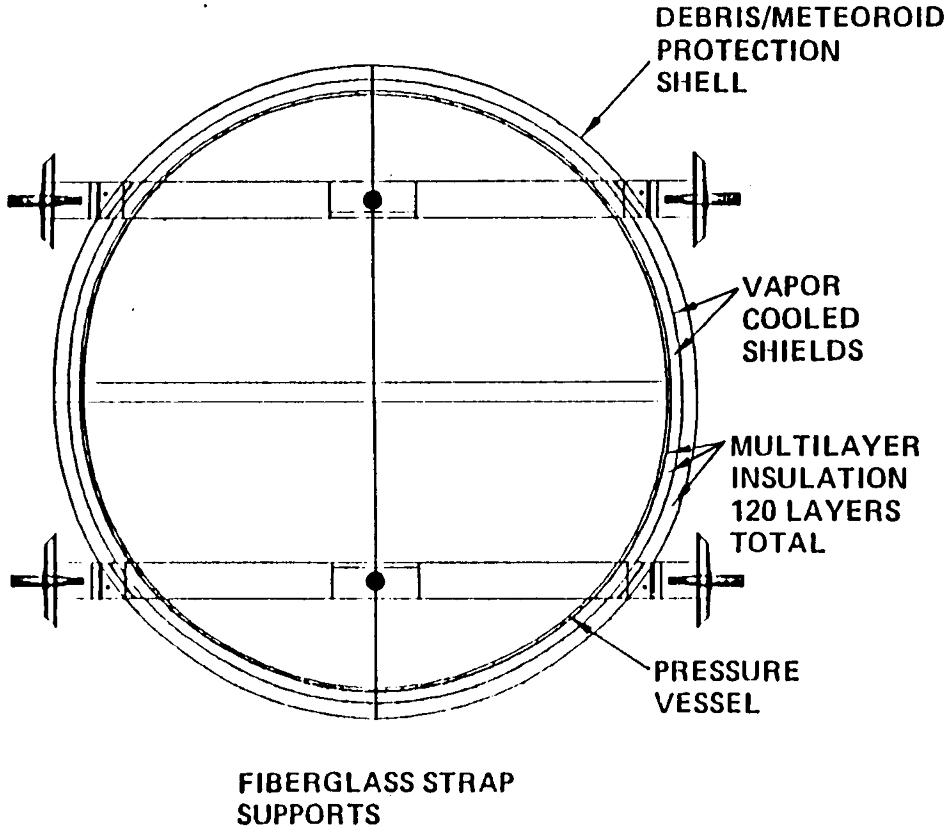

DESIGN PARAMETERS

- PRESSURE VESSEL
  - DIAMETER, 13 FT
  - LENGTH, 13.47 FT
  - WEIGHT, 438 LBM
- DEBRIS/METEOROID SHELL
  - DIAMETER, 14.33 FT
  - LENGTH, 14.8 FT
  - WEIGHT, 829
- CAPACITY AT 17.5 PSIA.
  - 79714 LBM WITH 7% ULAGE
- INSULATION SYSTEM
  - 120 LAYERS MLI
  - 2 VAPOR COOLED SHIELDS WITHIN MLI
  - BOILOFF, 13 LBM/DAY
- LIQUID ACQUISITION SYSTEM
  - 8 CHANNELS ON MERIDIANS
  - CHANNELS 4 IN. BY 1 IN.
  - 2 SCREENS 325 x 2300 ON ONE SIDE OF CHANNEL
  - WEIGHT, 260 LBM
- TOTAL TANK WEIGHT, 2063 LB
- ASE WEIGHT, 598 LBM
- DEVELOPMENT COSTS, $\$48.8 \times 10^6$
- PRODUCTION COST, $\$4.7 \times 10^6$

Figure 3.3-3 Space Station Oxygen Storage Tank Baseline Concept

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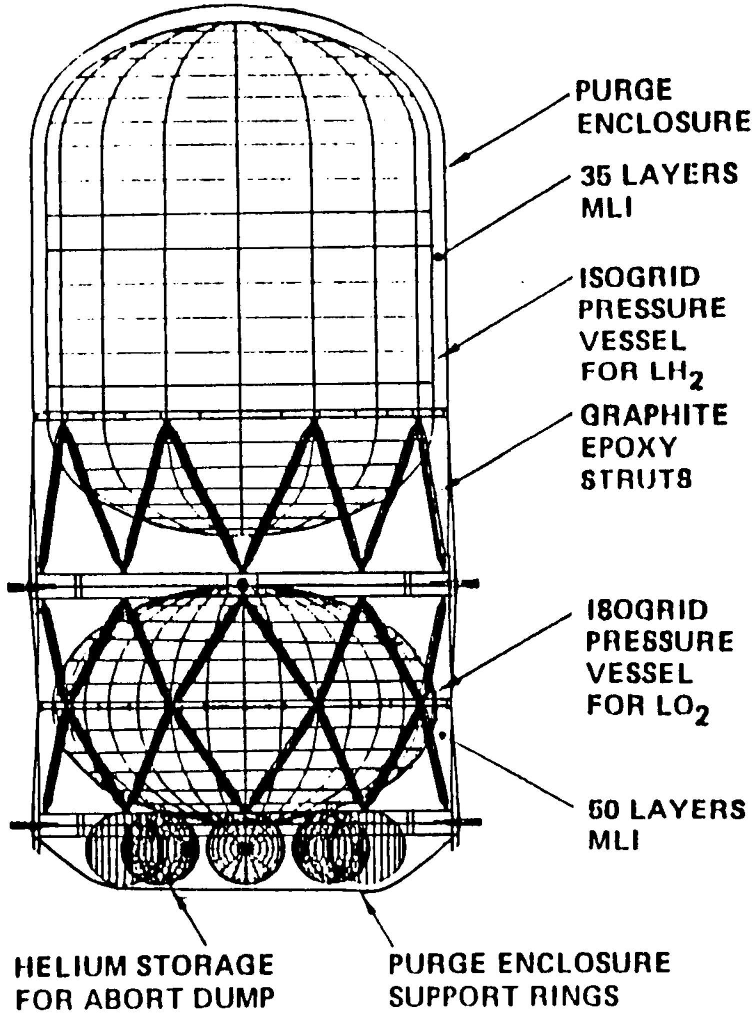
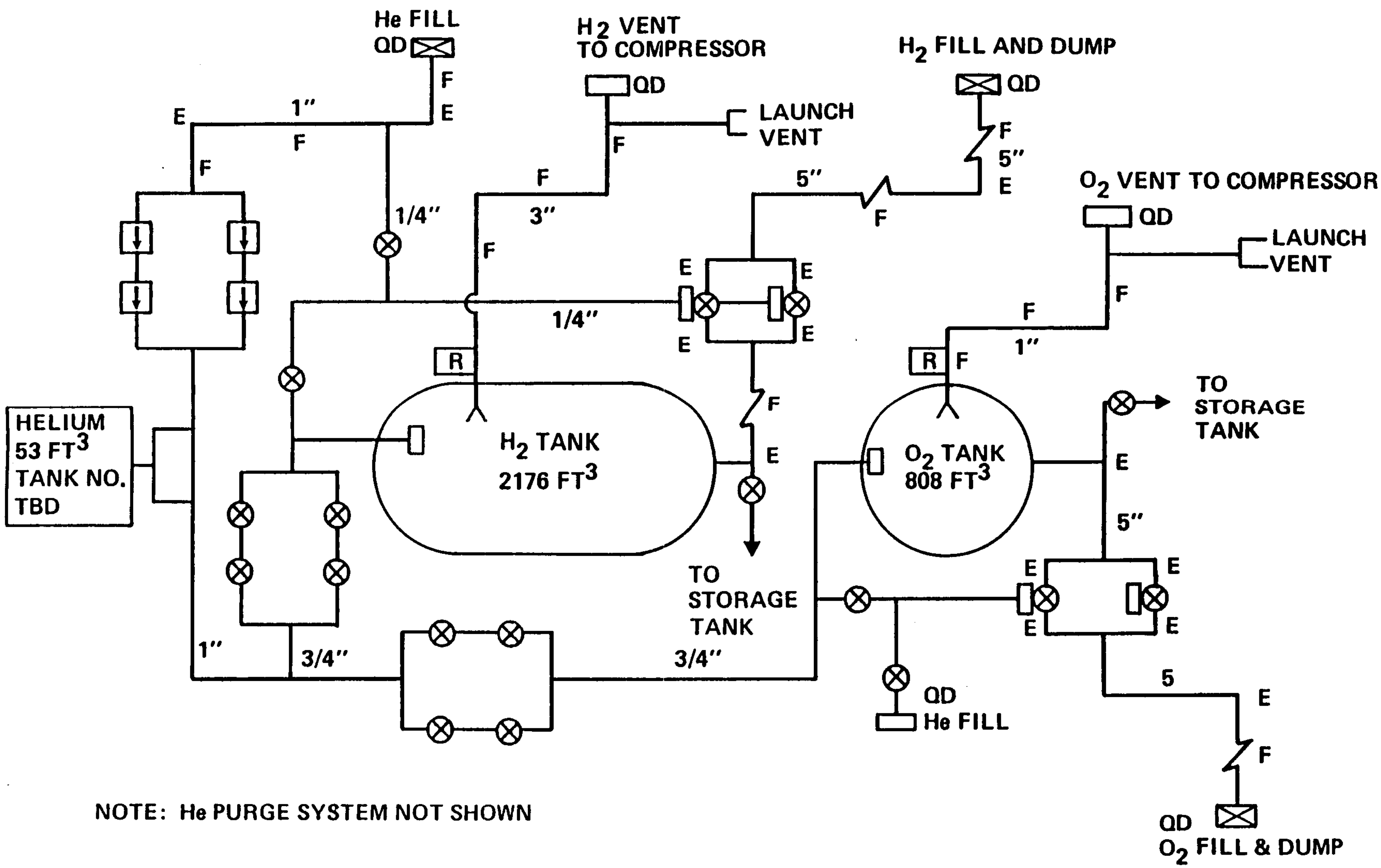


- TANKER DESIGN PARAMETERS
- HYDROGEN TANK
  - PRESSURE VESSEL
    - DIAMETER, 13.33
    - LENGTH, 19.23
    - WEIGHT, 1002
    - VOLUME, 2176 FT^3
  - CAPACITY AT 17.5 PSIA
    - 8858 LBM WITH 7% ULLAGE
  - INSULATION
    - HELIUM PURGED 35 LAYERS MLI
  - ACQUISITION SYSTEM WEIGHT 585 LBM
- OXYGEN TANK
  - PRESSURE VESSEL
    - DIAMETER, 13.33
    - LENGTH, 9.43
    - WEIGHT, 729
    - VOLUME, 808 FT^3
  - CAPACITY AT 17.5 PSIA
    - 53146 LBM WITH 7% ULLAGE
  - INSULATION
    - HELIUM PURGED 50 LAYERS MLI
  - ACQUISITION SYSTEM WEIGHT, 217 LBM
- HELIUM STORAGE
  - CAPACITY 124 LBM
  - 4000 PSIA
- TOTAL TANKER SYSTEM WEIGHT INCLUDING PLUMBING IS 6479 LBM
- DEVELOPMENT COST, \$195.5 X 10^6
- PRODUCTION COST, \$19.3 x 10^6 FIRST UNIT

Figure 3.3-4 Tanker Tanks Configuration Baseline Concept



NOTE: He PURGE SYSTEM NOT SHOWN

Figure 3.3-5 Tanker Plumbing System

OTV-424

in table 3.3-1. Based on the propellant logistics operations for the year 2001, 107.5 lbm of propellant must be delivered for every 100 lbm available to the OTV resulting in a 7.5% handling factor.

3.4 Implications of "No Vent" Requirement

The Space Station requirement of no fluid venting has major impacts on the storage and transfer of cryogenic fluids. The gases which must be captured and stored include boiloff and chilldown losses and OTV reserves and residuals returned to the station. Approximately 6,700 lbm of oxygen and 2,520 lbm of hydrogen will accumulate in a 90 day period. Assuming the gases are stored at 2,000 psia and 500 degrees Rankine, it would require ten 9 foot diameter pressure vessels for hydrogen storage and two 8 foot diameter pressure vessels for oxygen storage as shown by figure 3.4-1, if none of the gases are used for a 90 day period.

The storage requirements for the surplus gases could be reduced by using fuel cells to convert a fraction of the gases to water and produce net power of approximately 3.9 kw as shown in figure 3.4-2. The excess of hydrogen available above the fuel cells stoichiometric ratio would still require six 9 foot diameter pressure vessels if none were used in the 90 day period.

The no vent requirement also has a major impact on the propellant transfer line size and power requirement. Recovery of the line and chilldown loses is at a much higher rate than that associated with recovery of boiloff, reserves, and residuals. Figure 3.4-3 shows the energy required for compressing the gases assuming 70% compression efficiency. Approximately 0.21 kilowatt hours/lbm are required for hydrogen and 0.05 kilowatt hours/lbm are required for oxygen for the 2,000 psia storage pressure selected. The maximum power required is determined by the quantity of the chilldown and flashed gasses during loading and the time used to accomplish the chilldown and liquid transfer.

The total costs for loading the OTV with 55,000 lbm of propellants for line sizes of 1.5, 2.0 and 2.5 inch diameter is shown by figure 3.4-4. The 2.0 inch line diameter results in near minimum cost for 7 hours (optimum) of loading time regardless of the power available for chilldown with no consideration of the cost of providing the peak power. Figure 3.4-5 uses the 2.0 inch line diameter to determine the impact of peak power costing. Discounted costs for the power optimization trade are required because the power must be made available at the start of the program. The optimum power is between 15 and 20 kw and is relatively constant between these limits. A total OTV chilldown and loading can be accomplished in approximately 7.3 hours with 20 kw power

Table 3.3-1 Typical Annual (2001 Total Propellant Accounting and Handling Losses

EVENT	NET MASS (LBS)	LOST MASS (LBS)
TANKER DELIVERIES (7)	420,000	14,035
SCAVENGE DELIVERIES (13)	178,100	3,900
TOTAL DELIVERIES	598,100	17,935
STORAGE SYSTEM BOILOFF		14,600
OTV LOADINGS (9)	524,095	10,260
ORBITAL INVENTORY INCREASE	49,145	
OTV LOADING + INVENTORY INCREASE	573,240	
TOTAL ANNUAL LOSSES		42,795

- HANDLING FACTOR $= \frac{573240 + 42795}{573240} = 1.075$

⇨ FOR EVERY 100 LB PROPELLANT USED BY THE OTV, 107.5 LBS OF PROPELLANT MUST BE LAUNCHED.

OTV-636

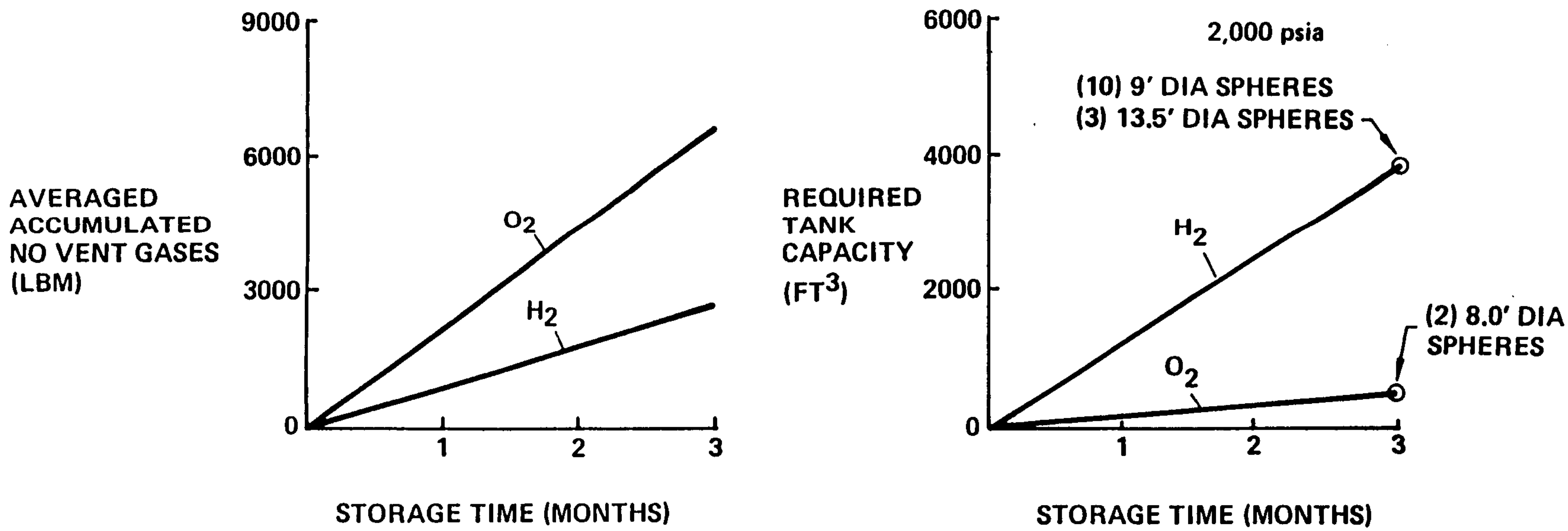


Figure 3.4-1 Storage Tank Sizing for "No Vent" Requirement

OTV-576

ELECTRICITY	DAILY SUPPLY, LBM H_2	DAILY SUPPLY, LBM O_2
BOILOFF (2 TANK SETS)	14.1	25.5
FLIGHT LOSSES AT 8 FLIGHTS/YEAR		
CHILLDOWN	7.8	12.3
RESERVES	4.1	24.0
RESIDUALS	2.0	12.5
TOTAL	28.0	74.3
NET AT STOICHIOMETRIC	9.36	74.3
POWER AVAILABLE AT 0.9 LB/KWH	3.9 KW	
NET WATER	83.7 LBM/DAY	
RESIDUAL H_2	18.6 LBM/DAY	
AVG. POWER FOR COMPRESSION	0.4 KW	
NET POWER AVAILABLE	3.5 KW	

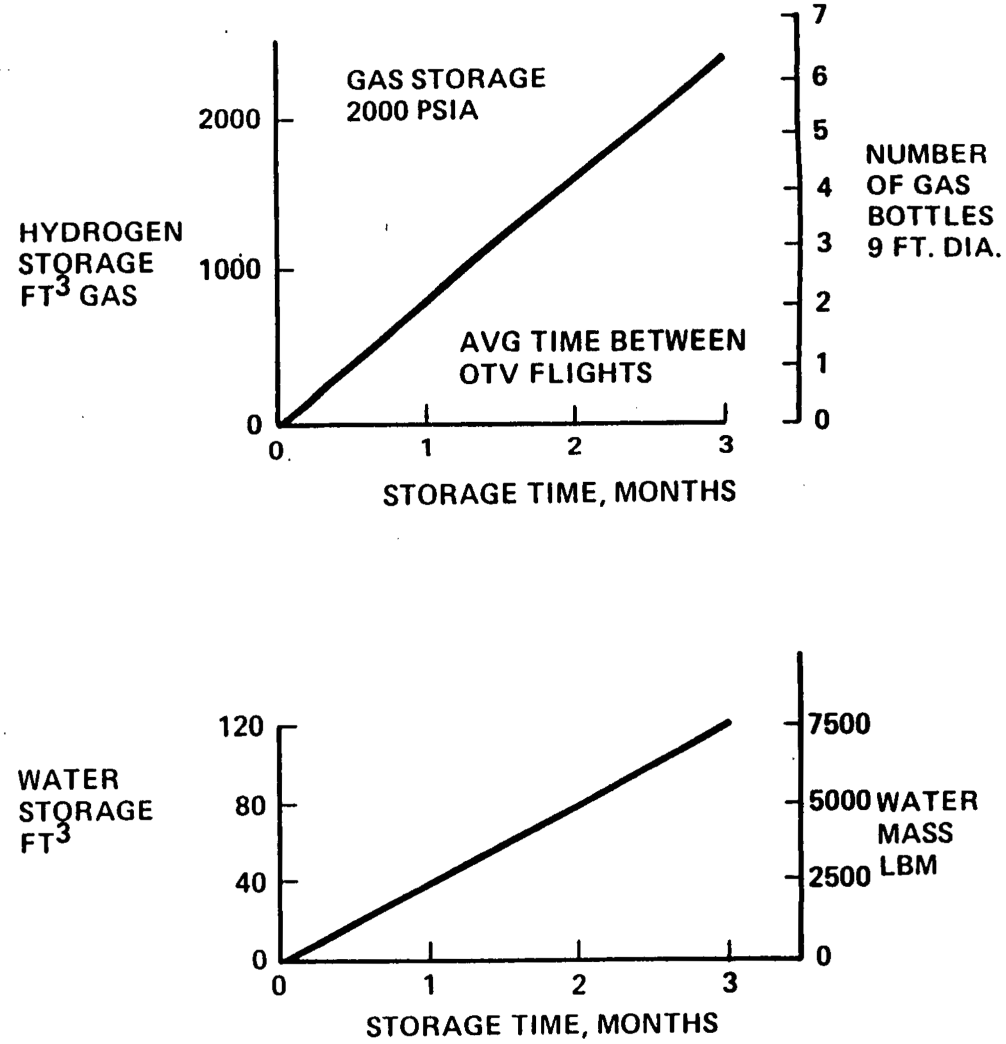
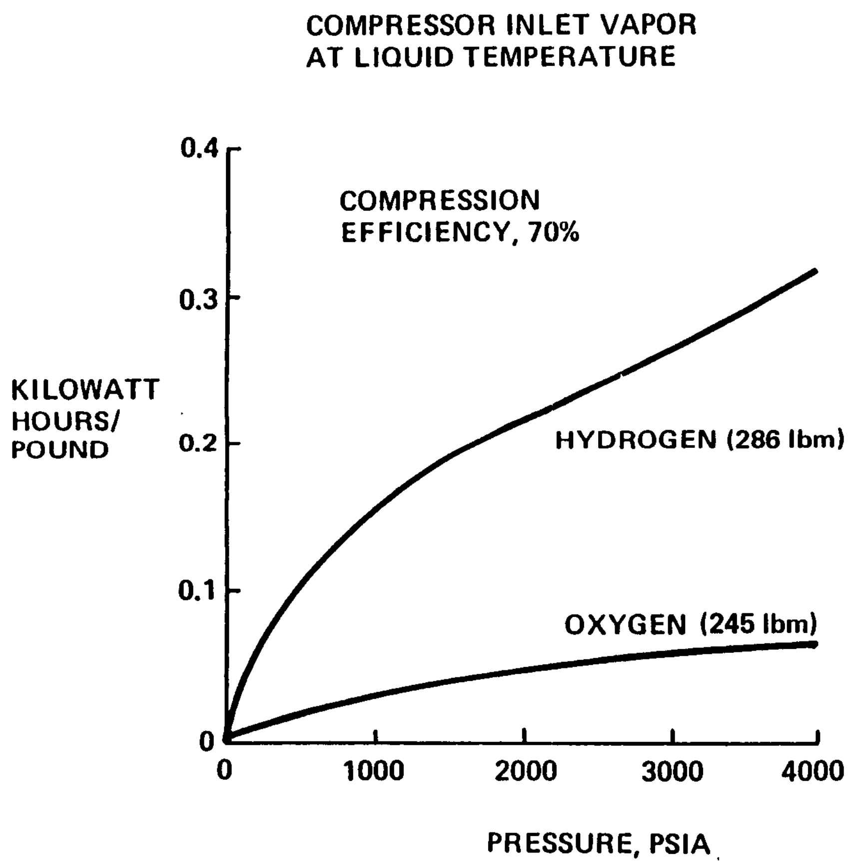


Figure 3.4-2 OTV Surplus Gas Use by Space Station

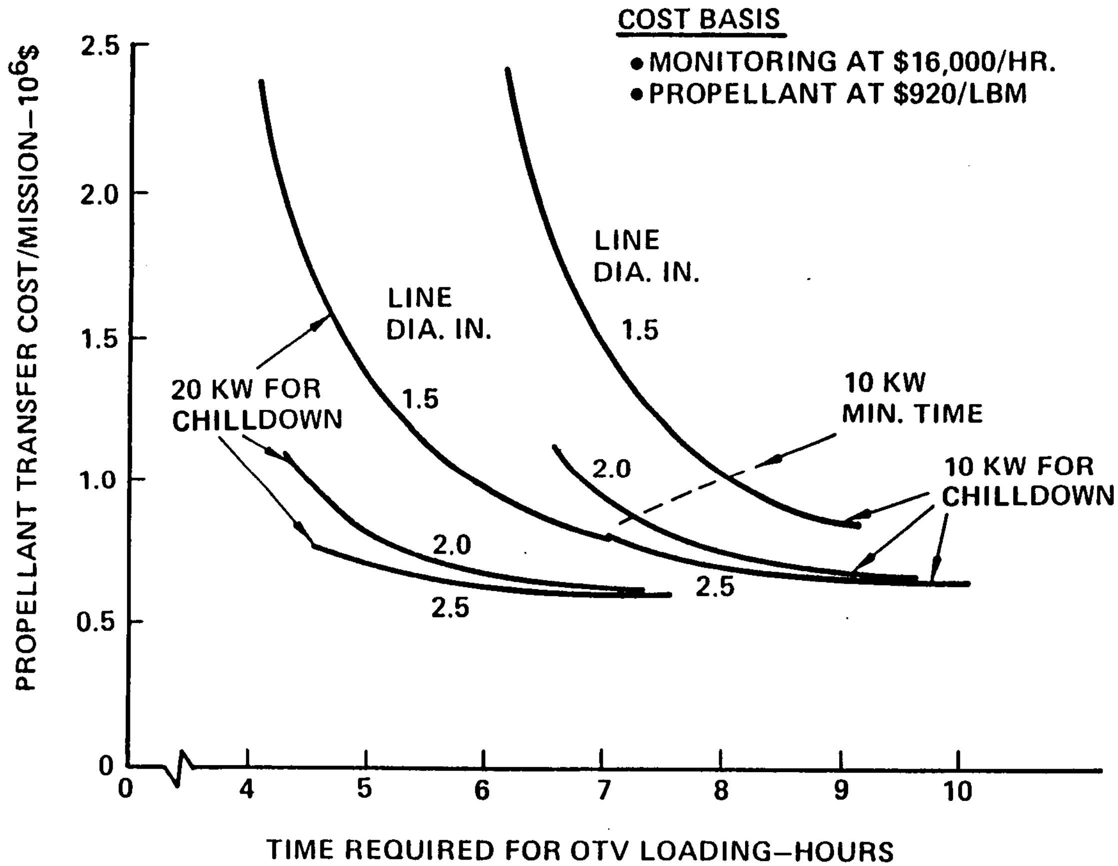
OTV-792



- FLUIDS AVAILABLE
  - HYDROGEN
    - OTV CHILLDOWN, 286 LBM
    - MISSION RESERVES, 132 LBM
    - MISSION RESIDUALS, 79 LBM
    - TOTAL, 497 LBM
  - OXYGEN
    - OTV CHILLDOWN, 245 LBM
    - MISSION RESERVES, 793 LBM
    - MISSION RESIDUALS, 472
    - TOTAL, 1510 LBM
- ENERGY REQUIREMENTS FOR 2000 PSIA STORAGE
  - 497 LBM HYDROGEN, 109 KWH
  - 1510 LBM OXYGEN, 76 KWH
- POWER REQUIREMENTS FOR 2000 PSIA STORAGE
  - OTV CHILLDOWN/FILL, 6 HOURS
    - HYDROGEN, 10.5 KW
    - OXYGEN, 2.05 KW
  - MISSION RESERVES AND RESIDUALS RECOVERED AT SLOWER RATES ARE NOT POWER CRITICAL

Figure 3.4-3 Recovery of OTV Reserves, Residuals and Cooldown Losses

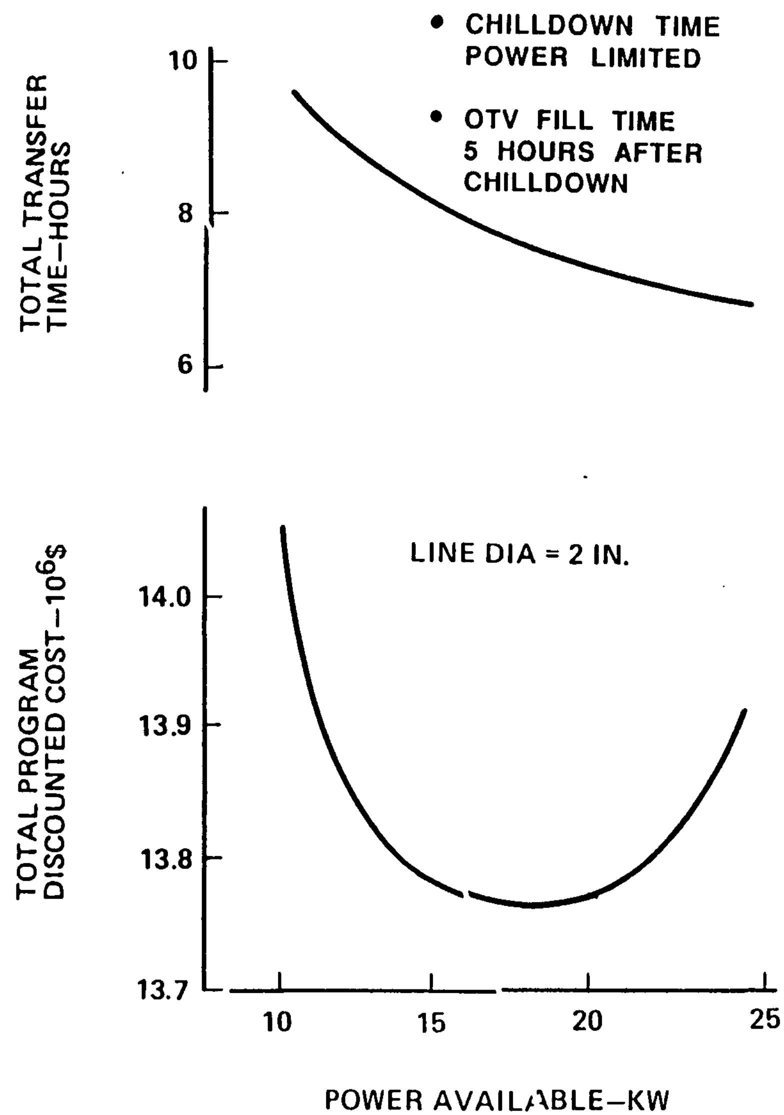
OTV-259



- LOADING TIME INCLUDES LINE AND OTV CHILLDOWN AND LOADING TIME 2 TO 5 HOURS.
- LOADING TIME IS LIMITED BY POWER AVAILABLE FOR "FLASHING" FOR 1.5 AND 2.0 IN. LINES WITH 10 KW POWER AVAILABLE.

Figure 3.4-4 Line Size Effects on OTV Propellant Fueling Costs

OTV-793



- COST BASIS
  - MONITORING AT \$16,000 /HR
  - PROPELLANTS \$920/LBM
  - POWER AT \$180,000/KW
  - DISCOUNTING AT10%/YEAR
  - 14 YEARS FOR 124 MISSIONS
- POWER OPTIMUM AT ~ 18 KW

Figure 3.4-5 Power Optimization for OTV Fueling

OTV-791

available for cooldown using 2.0 inch lines. The liquid flow time after chilldown is approximately 5 hours of the 7.3 hours total. The 5 hour flow time results in 108 lbm of flashing losses. Reducing the liquid flow time to 3 hours by increasing the tanks pressure difference completes the transfer in 5.3 hours but increases flashing losses to approximately 300 lbm which was used for propellant accounting.

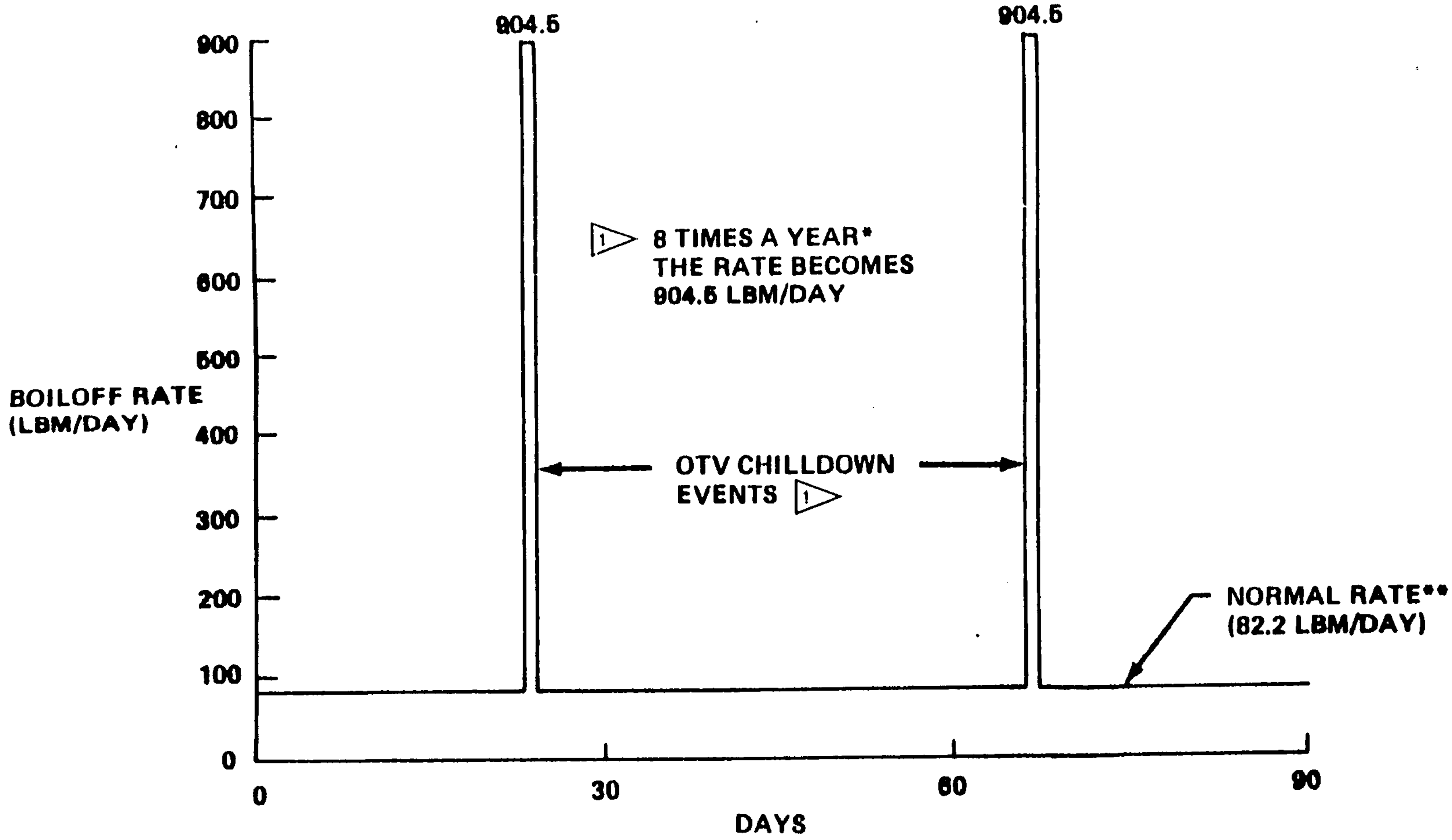
3.5 Boiloff/Chilldown Gas Disposition for SBOTV

A propellant excess of 7.6% over that required for the OTV flights is delivered to the Station by the propellant tanker. This excess is required because of boiloff from the storage tanks and losses due to propellant transfer lines and OTV tank chilldown. The disposition of these gases is a problem. Although NASA has stated that there is no longer a specific ground rule against venting at the Station, concerns expressed by many Station users are expected to preclude venting of quantities such as these resulting from SBOTV operations. In the analysis conducted, it has been assumed that venting at the Station will not be allowed.

The analysis conducted in the previous section concluded that boiloff and chilldown quantities indicated in figure 3.4-1 can be expected. The O_2 and H_2 accumulated over a 3 month interval is 6,687 and 2,520 lbm, respectively. It is apparent from this figure that, in terms of volume of gas that must be stored until disposal, GH_2 is dominant even at 2,000 psia (500°R). This analysis was conducted assuming 8 OTV flights per year. Scenario 2 of the Revision 9 mission model averages over 26 flights per year with a peak level of 33 per year in 1998 and 1999 and a low of 20 flights in 2003 (See Vol. IX). As shown in figure 3.5-1, OTV chilldown losses are 904.5 lbm/day so the additional launches will significantly affect the boiloff problem. However, this analysis was conducted consistent with the assumption of 8 flights per year. As will be seen, the problem is quite significant and costly to resolve at even this lower flight rate.

As indicated in figure 3.4-1, the GH_2 could be contained in either ten 9 foot diameter spheres or in three 13.5 foot diameter spheres (obviously, other diameters could be used but those selected represent reasonable extremes). Assuming both tanks are made of Kevlar-wrapped titanium with the necessary safety factors and the same ASE weight, the 3 tank approach weighs 7.5% more than the 10 tank approach. Consequently, the GH_2 storage approach using 10-9 foot diameter tanks has been adopted.

The tanks selected for containment of the 2000 psia GH_2 and GO_2 have the following characteristics:



*ASSUMED OTV FLIGHT RATE
**INCLUDES STORAGE TANK AND OTV RESIDUALS AND RESERVES BOILOFF

Figure 3.5-1 Unsteady Character of H_2/O_2 Boiloff Availability

OTV-1204

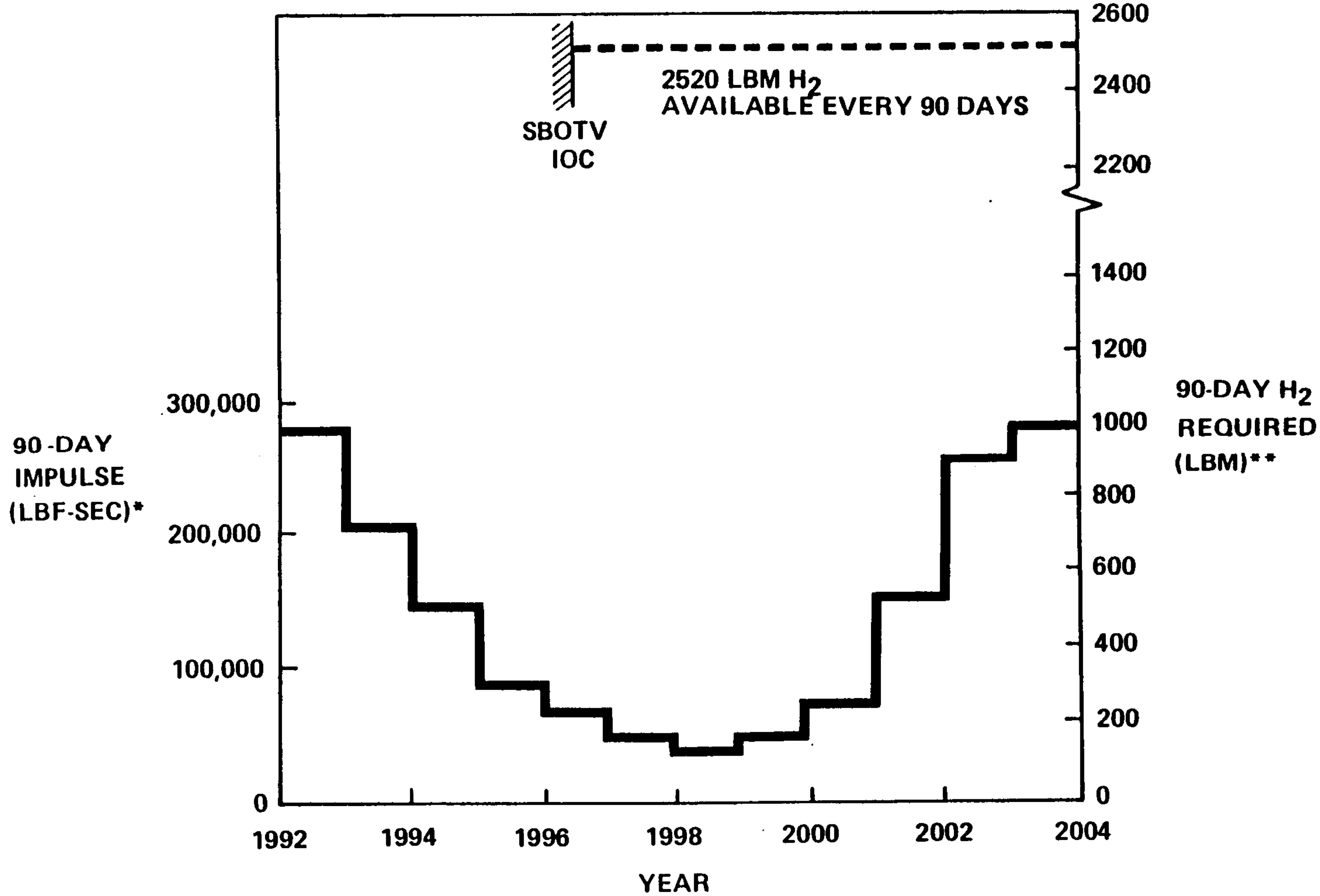
	GH_2	GO_2
Material	Kevlar on Titanium	Kevlar on Titanium
Thickness, Liner, Ave. (in)	0.12	0.088
Thickness, Composite, Ave. (in)	0.92	0.81
Tank Weight (lbm)	2870.0	2330.0
Diameter (ft)	9.0	8.0

The boiloff gas disposition options examined are summarized as follows.

Option No.	Description
1a	Collect GH_2 and GO_2 for periodic venting remote from the Station using the OMV.
1b	Collect GH_2 and GO_2 and periodically return these gases to the Earth using the Orbiter.
2a	Use the GO_2 and the required GH_2 in a fuel cell with electrical power and water as output. Periodically remotely vent the remaining GH_2 and the water using the OMV.
2b	Same as option 2a except return the remaining GH_2 and the water to the surface using the Orbiter.
3a	Provide extra LO_2 to make a stoichiometric mixture with the GH_2 and produce power and water in a fuel cell. Remotely vent the water using the OMV.
3b	Same as option 3a except return the water to the surface using the Orbiter.
4	Complete reliquefaction of boiloff and chilldown gases.

A valid question to ask at this time is: why isn't the use of these gases for Space Station reboost considered? Figure 3.5-2 illustrates the 90 day impulse requirements for a nominal atmosphere for the years 1992 through 2004 assuming a constant Station altitude of 250 nm. Shown on the right hand scale are the H_2 90 day requirements assuming an Isp of 280 lbf-sec/lbm. The assumed SBOTV IOC of 1996 is followed by the availability of 2,520 lbm GH_2 every 90 days. It is seen that the amount available far exceeds that required even in the peak year of 2004 when 1,000 lbm would be required. If the Station is operated at a constant density altitude instead of a constant geocentric altitude, the required GH_2 for reboost may be maintained at 1,000 lbm every 90 days.

Figure 3.5-3 summarizes, pictorially, the disposal options considered. The following paragraphs will discuss the options individually.



*NOMINAL ATMOSPHERE
**BASED ON H_2 COLD GAS THRUSTER, I_{SP}=280 LBF–SEC/LBM

Figure 3.5-2 Space Station Reboost Requirement and SBOTV H_2 Availability

OTV-1201

OTV-1203

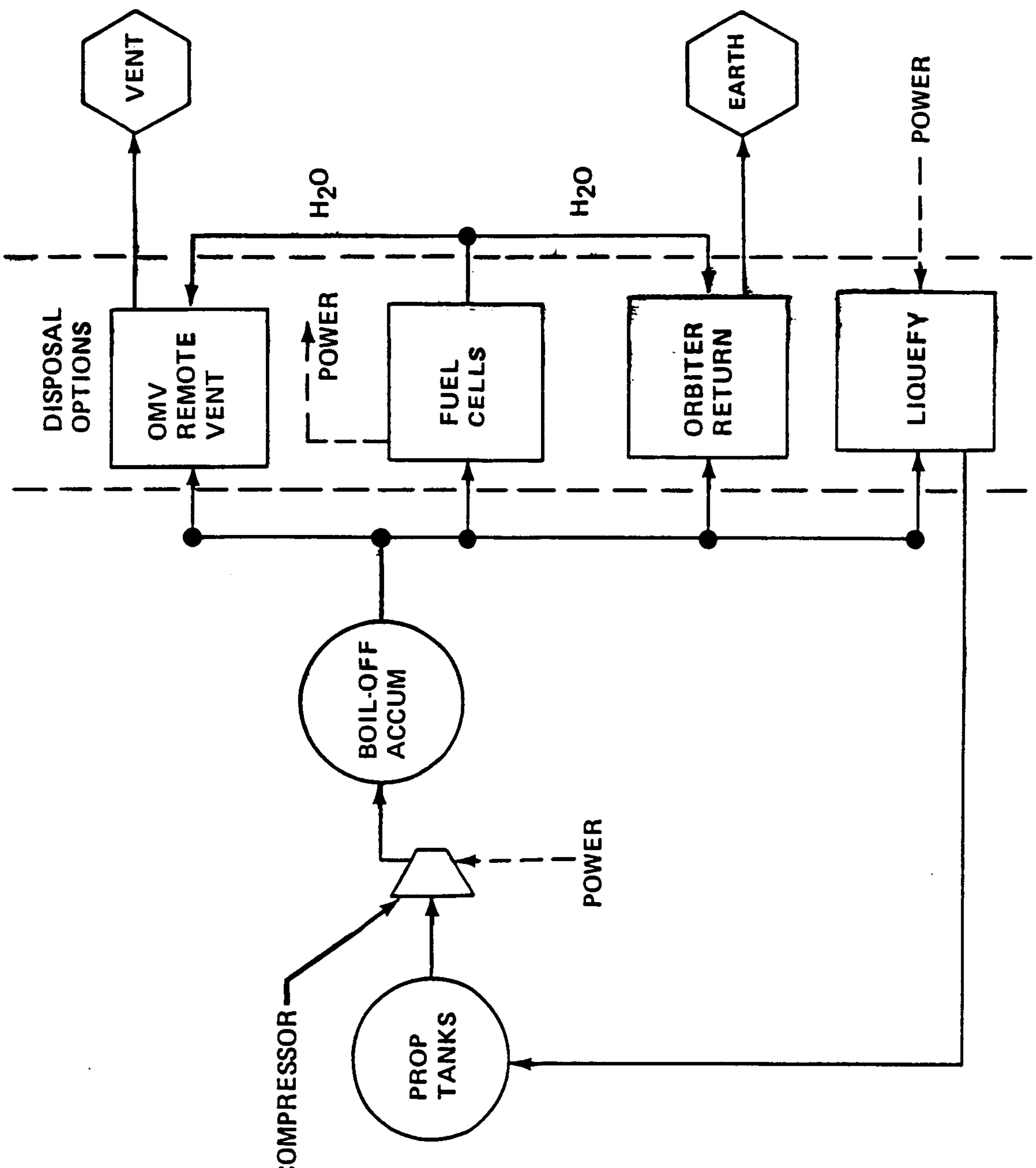


Figure 3.5-3 Boil Off/Chilldown Disposal Options

Option 1a, Remote Venting

This option utilizes the OMV to maneuver the 10 GH_2 and 2 GO_2 storage vessels to a location remote from the Station for venting. Figure 3.5-4 depicts the envisioned arrangement for the tanks and the dump system. The OMV, weighing 10,486 lbm and the waste package weighing 43,527 lbm, are accelerated to a delta V of 1 ft/sec from the Station using the OMV GN_2 thrusters.

After coast to preclude Station contamination, the vehicle is rotated 180° and accelerated an additional 2 ft/sec using the GH_2 dump nozzle on the vehicle centerline. After an additional coast to a sufficient distance for GH_2 and GO_2 dump, the vehicle is again rotated 180° and stopped relative to the Station (delta V = 3 ft/sec). The gases are then dumped except for sufficient GH_2 to provide the impulse to return to the Station. The total GH_2 required to accomplish these maneuvers is less than 50 lbm. The OMV GN_2 requirement is 52 lbm and the hydrazine system is not required.

Costs associated with this option are listed below:

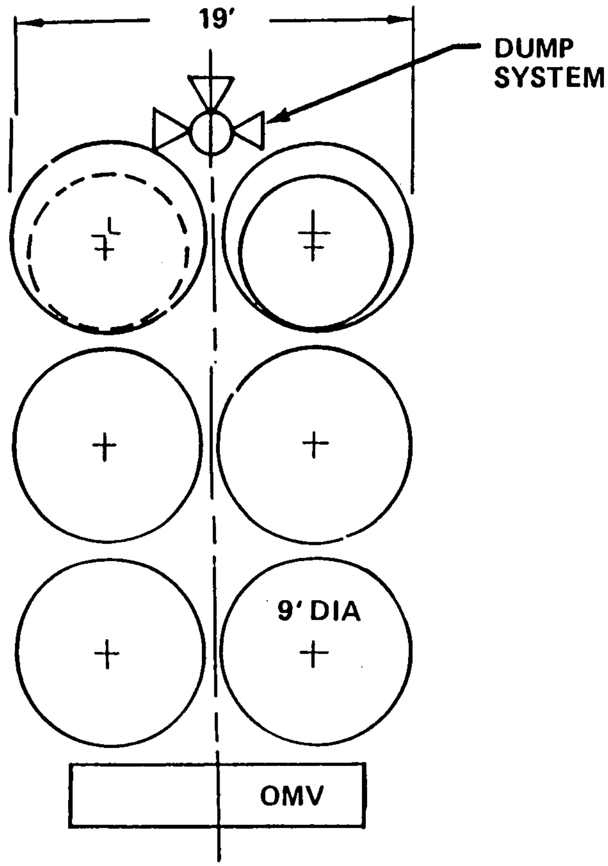
Recurring:		
OMV use charge	\$ 1.00M	
GN_2 (\$1500/lbm)	0.07M	
IVA (3.5 hrs)	0.06M	
EVA (3.0 hrs)	0.50M	(for OMV servicing)
TOTAL	\$ 1.63M	
Tank Delivery, One Time (\$1500/lbm):	42.58M	
DDT&E:	\$148.7M	
TFU:	\$63.5M	

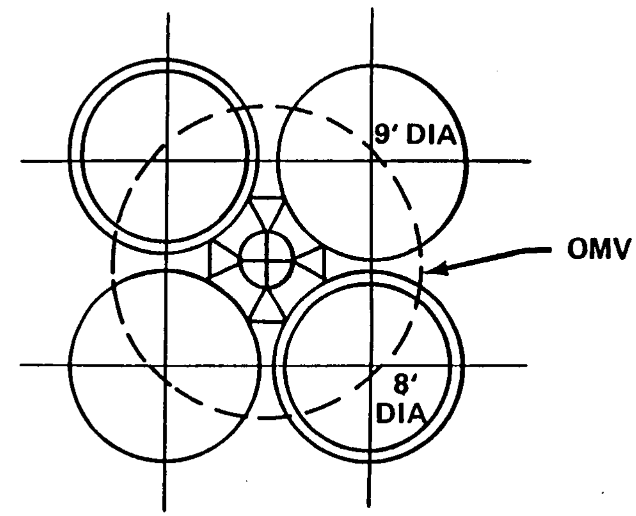
Option 1b, Boiloff Return via Orbiter

This option employs identical gas storage tanks as used for option 1a but carries the filled tanks to the earth using the Orbiter for gas disposal. Differences in the two approaches include no dump system, no OMV usage, and 2 storage tanks sets.

Costs associated with this option are:

Recurring:	
Tankset Delivery (\$1500/lbm)	\$42.58M
IVA (6 hrs)	0.11M
TOTAL:	\$42.69M
DDT&E:	\$225.8M
TFU:	\$63.2M





FEATURES

- GH_2 PROVIDES 75% OF ΔV THROUGH DUMP SYSTEM
- ALL REUSABLE HARDWARE

WEIGHT SUMMARY (LBM)

GH_2	2,520
GO_2	6,687
GH_2 TANKS (@ 2405)	24,050
GO_2 TANKS (@ 1689)	3,378
STRUCTURE	960
LAUNCH TOTAL	37,595

Figure 3.5-4 Remote Vent Options for Boiloff/Chilldown Gases

OTV-1202

Option 2a, GO_2 Usage for Power, Remote GH_2 and Water Vent

This option combines the available GO_2 (6687 lbm) with the required amount of GH_2 to make a stoichiometric mixture which is provided to fuel cells resulting in 1684 lbm GH_2 remaining, 7,532 lbm H_2O, and 3.87 KW. The result is that only 5 of the 9 ft. diameter GH_2 tanks are required and a 6.3 ft. diameter 2219 aluminum water storage tank with 0.025 inch thick walls, 20 psia, and weighing 55 lbm.

Disposal is accomplished by using the OMV as a carrier. Again, however, as was the scenario for option 1a, at least 75% of the delta V can be provided by the waste GH_2. In order to dump water, a heated nozzle will be required to prevent ice formation and resultant clogging. The Station can't use the water produced because the currently envisioned ECLSS will produce excess water without additions from an OTV source.

Costs associated with the option are listed below:

Recurring:		
OMV use charge	$1.00M	
GN_2 ($1500/lbm)	0.04M	
IVA (3.5 hrs)	0.06M	
EVA (3.0 hrs)	0.50M	(for OMV servicing)
SUBTOTAL	$1.60M	
Power Value ($326,000/KW):	-1.26M	
TOTAL	$0.34M	
Tank Delivery, One Time ($1500/lbm):	18.87M	
DDT&E:	$76.9M	
TFU:	$28.3M	

Option 2b, GO_2 Usage for Power, Return GH_2 and Water via Orbiter

This option is similar to option 2a except the remaining GH_2 and water are returned via the Orbiter. At least two tanksets will be required to have one constantly available at the Station.

Cost associated with this option are listed below:

Recurring:	
Tankset Delivery ($1500/lbm)	$18.87M
IVA (6 hrs)	0.11M
SUBTOTAL	$18.98M
Power Value ($326,000/KW):	-1.26M
TOTAL:	$17.72M
DDT&E:	$111.0M
TFU:	$28.1M

Option 3a, Generate Maximum Power, Provide Additional O_2 Remotely Vent Water

This option utilizes all available GH_2 to generate power by delivering an additional 13,473 lbm of LO_2 every 90 days. The power generated is 11.7 kw and the resultant water for a 90 day interval weighs 22,680 lbm. A 2219 aluminum tank to contain this water at 20 psia is 9.14 feet in diameter and weighs 110 lbm (0.025 inches average wall thickness). Associated plumbing and structure weight is 200 lbm.

The water tank package weighing 22,990 lbm is taken to a remote location using the OMV in a manner similar to options 1a and 2a. However, this option requires that all delta V be provided by the OMV. The total GH_2 requirement from the OMV 79.9 lbm. Again, the nozzle to be used for dumping water will have to be heated to prevent ice formation and nozzle clogging.

Costs associated with this option are:

Recurring:		
OMV use	$ 1.00M	
LO_2 Delivery ($1500/lbm)	14.66M	
GN_2 Delivery ($1500/lbm)	0.12M	
IVA (3.5 hrs)	0.06M	
EVA (3 hrs)	0.50M	(for OMV servicing)
SUBTOTAL	$16.34M	
Power Value ($326,000/KW)	-3.81M	
TOTAL	$12.53M	
Tank Delivery, One Time ($1500/lbm)	0.47M	
DDT&E	$2.6M	
TFU:	$1.1M	

Option 3b, Generate Maximum Power, Provide Additional O_2, Return Water in Orbiter

This option is similar to option 3a except that the tank of water is returned via the Orbiter. A second 110 lbm, 9.14 ft. diameter tank will be required to assure constant availability for water storage at the Station.

Costs associated with this option are:

Recurring:	
LO_2 Delivery (1500/lbm)	\$14.66M
Empty Tank Delivery (\$1500/lbm)	0.47M
IVA (4 hrs)	0.07M
SUBTOTAL	\$15.20M
Power Value (\$326,000/KW)	-3.81M
TOTAL	\$11.39M
DDT&E: \$3.6M	
TFU:	\$2.2M

Summary of Options 1 through 3

Figure 3.5-5 summarizes the costs for each of the options discussed thus far.

Option 4, Reliquefy Boiloff Gasses

The H_2 boiloff rate is 2,520 lbm every 90 days or, on the average, 1.17 lbm/hr. The O_2 boiloff rate is 6,687 lbm every 90 days for an average of 3.1 lbm/hr. An analysis of reliquefaction systems is beyond the scope of this study. A long life, high capacity, space qualified reliquefaction system has not been developed. Several studies have been conducted recently to address this issue (e.g., AFRPL TR-83-082, "Long Term Cryogenic Storage Study", and NAS8-36612, "Long Term Cryogenic Storage Facility Systems Study"). A system to reliquefy only the H_2 boiloff will be discussed and costed herein. It will be seen that this alone makes the reliquefaction approach unattractive barring significant technology advances.

Based on data from NASA Conference Bulletin 2347, a Turbo Brayton Cycle refrigerator capable of reliquefying 1.17 lbm/hr will require 4 kw. NBS Tech. Note 655 (June 1974) shows that a 4 kw H_2 Brayton cycle reliquefaction system will weigh 44,100 lbm.

Costs associated with the (H_2 only) reliquefaction option are:

OPTION	BOIL OFF & CHILLDOWN STORAGE TANKS (90 DAYS)									POWER GEN. KW	DISPOSAL MODE	COST ($M)				
	H_2			O_2			H_2O									
	NO.	DIA FT	WT LBM	NO.	DIA FT	WT LBM	NO.	DIA FT	WT LBM			RECURRING PER FLIGHT	ONE TIME DELIVERY	DDT&E	FIRST UNIT	LCC *
1	10	9	2405 EACH	2	8	1689 EACH	–	–	–	–	1a. OMV	1.63	42.6	148.7	63.5	359.1
											1b. ORBITER	42.7	–	225.8	63.2	3085.0
2	5	9	2405 EACH	–	–	–	1	6.3	55	3.87	2a. OMV	0.34	18.9	76.9	28.3	145.9
											2b. ORBITER	17.7	–	111.0	28.1	1300.0
3	–	–	–	–	–	–	1	9.14	110	11.7	3a. OMV	12.5	0.47	2.6	1.1	803.7
											3b. ORBITER	11.4	–	3.6	1.1**	735.4

*BASED ON 64 DISPOSAL FLIGHTS OVER 16 YEARS, UNDISCOUNTED
**THE ORBITER OPTION REQUIRES A SECOND UNIT WHICH HAS BEEN INCLUDED IN THE LCC, THE OMV OPTION REQUIRES A SINGLE UNIT.

Figure 3.5-5 Boil Off/Chilldown Disposition Trade

OTV-1200

Recurring:	
Power (at $326,000/KW)	$1.30M
Propellant Saved ($1500/lbm)	-3.78M
TOTAL RECURRING	$-2.15M
Reliquefaction System Delivery ($1500/lbm)	66.15M
DDT&E (including first unit):	$639.5M

Cost Summary and Recommendation

Figure 3.5-6 summarizes the undiscounted LCC for the boiloff disposal options. The clear winner and recommended approach is option 2a, which uses half of the GH_2 to generate 3.87kw. The remaining GH_2 and the resulting water are remotely vented using the OMV.

Significant advances are being made in the development of reliable, low cost, and lightweight cryogenic reliquefaction systems suitable for the Space Station application. These advances have the promise of altering the foregoing study toward the reliquefaction option.

3.6 Summary

The optimum cryogenic oxygen and hydrogen logistic system using a storage depot at the Space Station was identified by the trade studies conducted. Major elements of the optimized system are two oxygen and two hydrogen dewars permanently based at the Space Station. The total capacity of the dewars is 186,000 lbm of oxygen and hydrogen at a mixture ratio of 6/1. The propellant capacity is adequate to support a manned mission with reserve available for backup rescue if required. Resupply of propellants to the Space Station uses an Orbiter-launched tanker with MLI insulation. The optimum system resulted in only slightly lower total program costs than the next lowest cost system which used a dewar type tanker configuration with tanks exchanged at the Space Station. Both systems are viable approaches to supplying OTV propellants at the Space Station.

Propellant losses due to boiloff and fluid transfers with the selected baseline system are not excessive. Based on the propellant logistics operations for the year 2001, 107.5 lbm of propellant must be launched for every 100 lbm available to the OTV with the difference being the propellant handling losses.

Perhaps the most significant propellant logistics issue existing at this time is the implication of the "no vent" requirement at the Space Station. It has been shown that there is a significant impact regarding storage requirements as well as power needs for

APPROACH	DISPOSITION OPTIONS	UNDISCOUNTED LCC
1. 10 GH_2 & 2 GO_2 2000 PSI TANKS	a. OMV b. ORBITER	\$ 359.1M \$3085.0M
2. 5 GH_2 2000 PSI TANKS, 1 H_2O TANK ,GENERATE 3.87 KW	a. OMV b. ORBITER	\$ 145.9M \$1300.0M
3. 1 H_2O TANK, GENERATE 11.7 KW	a. OMV b. ORBITER	\$ 803.7M \$ 735.4M
4. RELIQUEFACTION AT THE STATION (4.0 KW; 44,100 LBM)	• N. A.	\$ 547.0M

CONCLUSION:	USE GO_2 TO GENERATE 3.87KW AND DISPOSE OF REMAINING GH_2 AND H_2O WITH AN OMV DELIVERY TO REMOTE SITE FOR VENTING

Figure 3.5-6 Boil Off/Chilldown Disposition Summary

OTV-1206

propellant transfer. A number of approaches for disposing of the boiloff and chilldown gases have been examined and compared on the basis of life-cycle-cost (LCC). The lowest LCC approach proved to be one that used the available O_2 and the required H_2 to make a stoichiometric mixture which was passed through a fuel cell to generate 3.87 kw. The remaining H_2 and the resulting water is disposed of remotely from the station using the OMV.

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4.0 FLIGHT OPERATIONS

This section describes the major generic flight operations that appear in all typical OTV mission sequences. Examination of the DRM's showed the flight operations of each OTV mission to be composed of five different flight segment types: 1) pre-flight and post-flight operations, 2) separation and rendezvous maneuvers, 3) orbital transfer/coast, 4) payload delivery and operations, and 5) aeromaneuver. Many of these operations are common to all DRM's, while others are more mission-specific. The operations identified above are also discussed elsewhere in the final report, specifically in Volume II, Book 1, Section 3.1. The summary discussion below is intended to put each flight operation in perspective with respect to the overall mission. Specific flight operation sequences, timelines, and delta V's are given in Volume II, Book 1, Section 2.4: Design Reference Missions. Figure 4.0-1 shows a typical mission profile.

4.1. PRE-FLIGHT AND POST-FLIGHT OPERATIONS

The OTV pre-flight and post-flight operations are summarized here for both ground- and space-based vehicles. Additional detail has been provided in Section 2.0. Pre-flight operations for the GB OTV include ground operations and the ascent to LEO in the Shuttle Orbiter and post-flight operations include return to earth and refurbishment. Preflight and postflight operations for the SB OTV are performed at the Space Station.

GB OTV. Following checkout, the GB OTV, its airborne support equipment, and its payload are mated and undergo integrated tests. The integrated assembly is then transferred to the launch pad and installed in the Shuttle Orbiter where propellant loading of the launch vehicle and the OTV are accomplished. Following launch and circularization to a 120 nautical mile orbit with an inclination of 28.5°, the Orbiter payload doors are opened and the OTV undergoes a predeployment checkout. The GB OTV is then deployed.

Post-flight operations begin when the OTV is returned to the Orbiter payload bay using the remote manipulator system, latched into the airborne support equipment structural adapter, stowed into the payload bay, and returned to the launch site for subsequent refurbishment for a later flight.

During the period that the OTV is within the Orbiter payload bay, command and control is accomplished by GSE and Orbiter systems prior to launch and through Orbiter systems after launch. When deployed outside the Orbiter, command and control is accomplished by a STDN/TDRS compatible RF link. The OTV is capable of autonomous

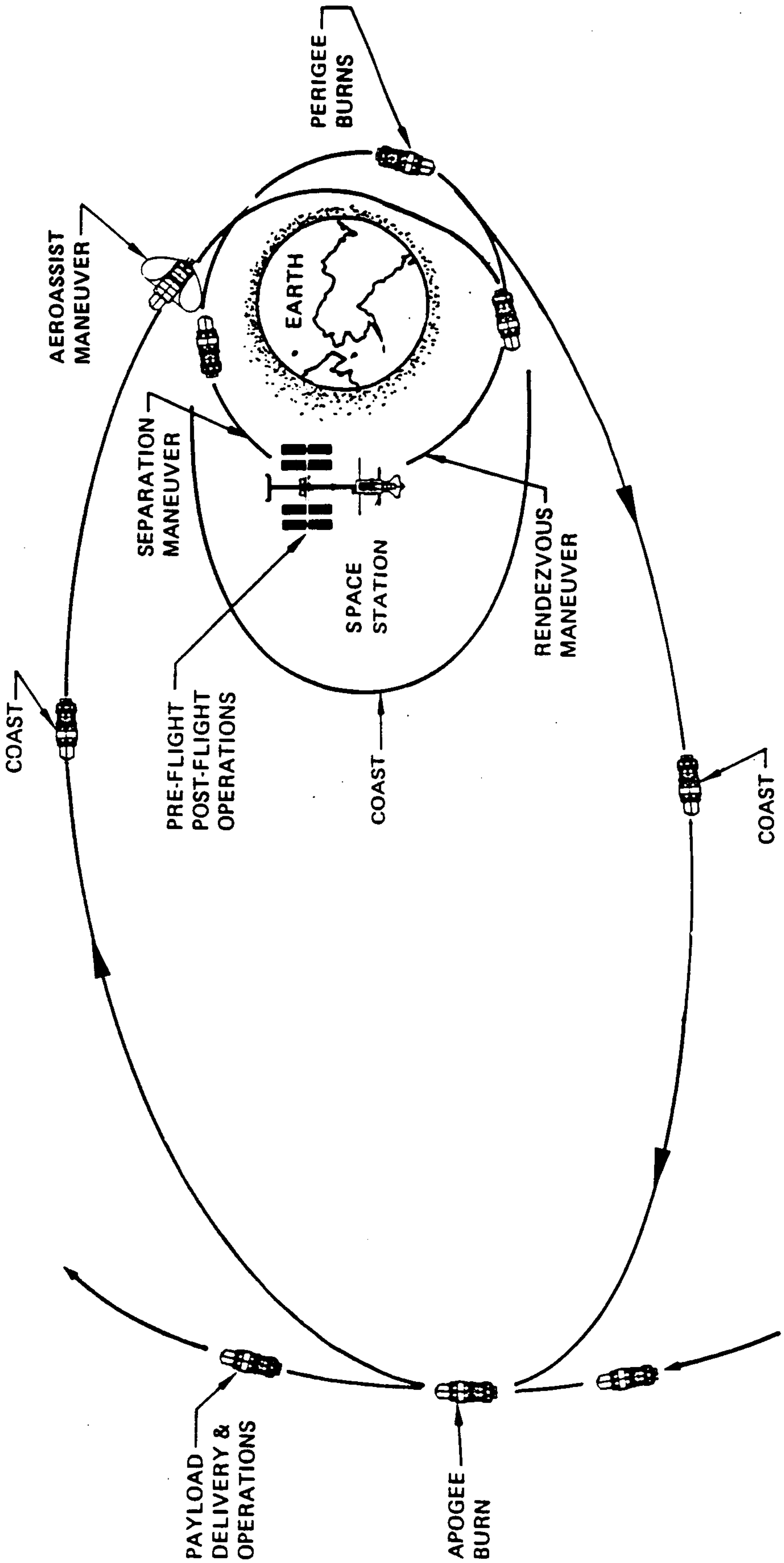

Figure 4.0-1. OTV Mission Profile

mission operations and is capable, by addition of a kit, of providing a secure communication link if required.

An additional preflight operation occurs when the GB OTV requires use of an auxiliary propellant tank (APT). This situation occurs on 36 of the 145 flights in the low mission model. These operations consist of the auxiliary propellant tank and payload combination being delivered to the Space Station followed by delivery of the OTV. Space Station personnel and equipment are used to perform physical integration of the OTV and APT/payload, verify interfaces, and perform launch operations.

SB OTV. The SB OTV is mated with its payload at the Space Station (270 nmi, 28.5° orbit). Integrated tests, propellant loading, and pre-deployment checkouts are also performed at the Space Station. The SB OTV is not ready for deployment until the Space Station reaches the proper ascending node alignment (to reach the proper GEO longitude). This differs from the GB OTV where the phasing operation is done after deployment from the Orbiter.

The SB OTV post-flight operations begin after OTV capture by the OMV in LEO. The OMV returns the OTV to the Space Station where it is secured and separated from the OMV. This is followed by post-flight checkout and refurbishment.

4.2 SEPARATION AND RENDEZVOUS MANEUVERS

Separation and rendezvous maneuvers occur at the beginning and end of each OTV mission from/to a launch platform (Space Station or Orbiter, depending on whether the OTV is space- or ground-based). The separation maneuver involves the actual process of separating from the launch platform and the coast period prior to main engine ignition. The rendezvous maneuver involves the period from the aeromaneuver to actual retrieval by the launch platform. The rendezvous/separation maneuvers associated with manned GEO operations (i.e., MGSS) have not been investigated.

Launch and retrieval are both conducted via an RMS grapple interface with STS/RMS or OMV/RMS. After separation, the OTV coasts and positions itself for its first transfer orbit injection burn. During this period and throughout the mission the OTV is in communication with its control center. In the case of a GB OTV, this coast period may include a number of phasing orbits.

The rendezvous coast period includes a number of MPS burns required to correct errors in altitude, velocity, and inclination. Its guidance system also requires GPS position updates.

Capture by the OMV or Orbiter is facilitated by radar corner reflectors. Active rendezvous by the OTV would require the addition of a rendezvous radar system (this may be required for MGSS rendezvous).

4.3 ORBIT TRANSFER/COAST

Most of the OTV mission time is spent either in a transfer orbit (e.g., LEO to GEO) or in a destination orbit (e.g., GEO). Transfer orbit operations is characterized by one or more MPS burns, each followed by a coast period, terminating with either an MPS burn (e.g., upleg, GEO phasing) or an aeromaneuver (downleg). Requirements for the transfer orbit include position and orientation of the OTV prior to MPS burns, the MPS burns, maintenance of orbital parameters during coast including RCS mid-course correction, and maintenance of vehicle attitude during coast (e.g., payload thermal roll).

The typical upleg transfer orbit has two perigee burns, a midcourse correction, and an apogee circularization/plane change burn. The typical GEO phasing orbit has a small MPS phasing burn, a midcourse correction, and a small MPS circularization burn. The typical downleg transfer orbit has a de-orbit/plane change burn, and a midcourse correction, leading up to the aeromaneuver. The exception to this is the planetary mission (DRM-3), where the payload is deployed (on an escape trajectory) on the upleg and the OTV is immediately decelerated to allow return to Earth.

4.4 PAYLOAD DELIVERY AND OPERATIONS

When the OTV reaches its target orbit it can either deploy its payload or initiate a mission operations sequence, such as rendezvous and dock with MGSS. The payload deployment is preceded by an ACS positioning maneuver. The payload is then activated by the OTV (timing discretes are one of the few OTV payload services) and released. The OTV then backs off and begins a coast period while waiting for the proper nodal alignment for return to LEO.

The manned missions have different operational sequences. With GEO servicing (DRM-4) the OTV rendezvous and docks with the MGSS where it remains active but under MGSS control for the duration of the GEO operations. With the manned lunar sortie the operational sequence is similar to the Apollo mission profile. After circularization in lunar orbit part of the crew transfers to an expendable lunar excursion module (LM) for descent to the lunar surface. The OTV with its manned capsule functions as the command module until the luner module returns from the surface and the whole crew returns to Earth in the OTV.

Missions in which the OTV picks up a payload in the target orbit for return to LEO were not identified in the mission model and so were not analyzed.

4.5 AEROMANEUVER

An aeromaneuver is performed on the return leg of each OTV mission. The aerobrake increases the OTV drag coefficient and provides thermal isolation so the OTV can use atmospheric drag to dissipate excess kinetic energy rather than slow the vehicle all-propulsively. The aeromaneuver is preceded by an alignment burn (prior to atmospheric entry) and followed by a correction burn to compensate for errors and atmosphere variations. Both of these burns require GPS navigation inputs. The OTV must navigate completely autonomously during the aeromaneuver itself because communications are interrupted during the atmospheric pass.

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